Final Report - January 22, 1999

JPL D - 16500

# *BIOMORPHIC EXPLORERS*

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## BIOMORPHIC EXPLORERS

Biomorphic explorers are small, dedicated, low-cost explorers that capture some of the key features of biological systems. These features include versatile mobility, distributed operations, and cooperative behaviors. Significant scientific payoff at a low cost is realizable by using the power of a large number of cooperatively functioning units. This study presents a classification of these explorers with example candidates in each category. Biomorphic Glider, a candidate biomorphic flight system, is selected for providing a combination of low mass (< 100 g), high payload fraction (> 50%), and large terrain coverage of 50-100 Km in 10 minutes. A variety of cooperative mission scenarios are discussed, showing the applicability of the glider to multiple missions. Then the study focuses on conceptual system design of a baseline Biomorphic Science Glider. Specific science objectives targeted for these missions include atmospheric info gathering by distributed multiple site measurements, close-up imaging for geological site selection, and deployment of surface payload such as instruments/crawlers-biomorphic surface systems/surface experiments. Candidate examples of measurement instrument payload, both atmospheric and imaging, along with imaging strategies to obtain stereo images with high spatial resolution are discussed. Spatial resolution ~ 0.5 cm is achievable with pictures taken in flight at an altitude of 50 m. Communication between the cluster of biomorphic gliders, the local relay (probeshell, lander, tethered balloon) and the orbiter is crucial to attaining the science objective. Telecommunication innovations such as monolithic chip transciever integration and amorphous glider interlink networks that are self-adaptive to obtain optimal data down link are suggested. A technology roadmap for realization of specifically biomorphic gliders in the near term and biomorphic explorers in the long term is presented.

## CONTENTS





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***This work was sponsored by the National Aeronautics and Space Administration***



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# EXECUTIVE SUMMARY

Inspired by the immense variety of naturally curious explorers (insects, animals, and birds), their well-integrated biological sensor-processor suites, efficiently packaged in compact but highly dexterous forms, and their complex, intriguing, cooperative behavior, this study focuses on "Biomorphic Explorers" and presents cooperative biomorphic planetary exploration scenarios. Biomorphic explorers are defined as small, dedicated, low-cost explorers that capture some of the key features of biological systems. These include versatile mobility, adaptive distributed controls and cooperative behavior. Biomorphic explorers offer the potential to obtain significant scientific payoff at a low cost by utilizing the power of a large number of cooperatively functioning units. This is analogous to operational principles of navigation and inter communication used by insect groups such as honey bees and ants.

A classification of these explorers based on their mobility ambient/environment divides them broadly into biomorphic flight systems and biomorphic surface/subsurface systems. Another classification is based on size/volume envelope/mass. Three general overlapping categories: 'A' = 1 to 20 cc, < 20g; 'B' = 10 to 200 cc, < 200g; 'C' = 100 to 2000 cc, < 2000g are defined. Example candidates in each category are presented. Such biomorphic explorers can potentially enable new capabilities in cooperative mission scenarios along with orbiters, landers, rovers, and/or balloons. Biomorphic flight systems, in particular have the potential for substantially higher mobility (in speed, range, and terrain independence). Biomorphic flight systems can even be made to deliver instrument payload/other biomorphic explorers to target sites, greatly extending the utility of those explorers. Cooperative exploration with an orbiter, lander/balloon, a rover, and a multitude of inexpensive biomorphic explorers would allow comprehensive exploration at a low cost and with broad spatial coverage. For orbiters, landers, rovers, and manned missions, flight systems in particular provide a means for exploring beyond the visual range of on-board cameras. They aid in identifying targets of scientific interest and to determine optimal pathways to those targets. The biomorphic flight system itself can be designed to seek out features of interest, crash at the target site, and then act as a homing beacon for further experiments. An important application is to use them as scouts in future planetary exploration where they would look for samples/sites of interest ~~from~~ in locations inaccessible to date. Specific focus of the mission concepts described in this study therefore are the biomorphic flight systems in the size B regime, namely biomorphic gliders, seedwing flyers, and powered flyers. Considerations of low mass, long range, and high payload mass fraction led to the choice of the glider as the candidate for conceptual system design. For example, the Biomorphic Glider provides a combination of low mass (<100 g), high payload fraction (> 50%) and large terrain coverage of (50-100 Km in 10 minutes).

The mission concepts developed in this study are targeted towards the following key objectives: (1) Atmospheric Info Gathering: Distributed Multiple Site Measurements, (2) Close-Up Imaging, Exobiology Site Selection, (3) Deployment of Payload: Instruments/Crawlers, etc. and (4) Sample Return Reconnaissance Mission. This study shows that Biomorphic glider missions can be implemented in several different scenarios because of their low mass and hence can be sent rapidly in the mass reserves of upcoming orbiter, lander, or balloon missions. The study concludes that biomorphic explorers is a technology push on
(1) miniaturization & integration of payload,
(2) cooperative communication innovations such as monolithic transciever integration and dynamic networks of self-routing optimal comm-interlinks,
(3) biomorphic flight systems, and
(4) biomechatronic surface system innovations.

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BIOMORPHIC EXPLORERS

# WHAT ARE BIOMORPHIC EXPLORERS?

- SMALL, DEDICATED, LOW-COST EXPLORERS THAT CAPTURE SOME OF THE KEY FEATURES OF BIOLOGICAL EXPLORERS
  - VERSATILE MOBILITY: surface, aerial, subsurface, fluids
  - ADAPTIVE, DISTRIBUTED OPERATION
  - BIOMORPHIC COOPERATIVE BEHAVIOR
- CONDUCTED WORKSHOP, AUG 19-20, 1998
  - SPONSORED BY TAP, SESPD, CISM, NMP
  - VERY SUCCESSFUL; OVER 150 PARTICIPANTS

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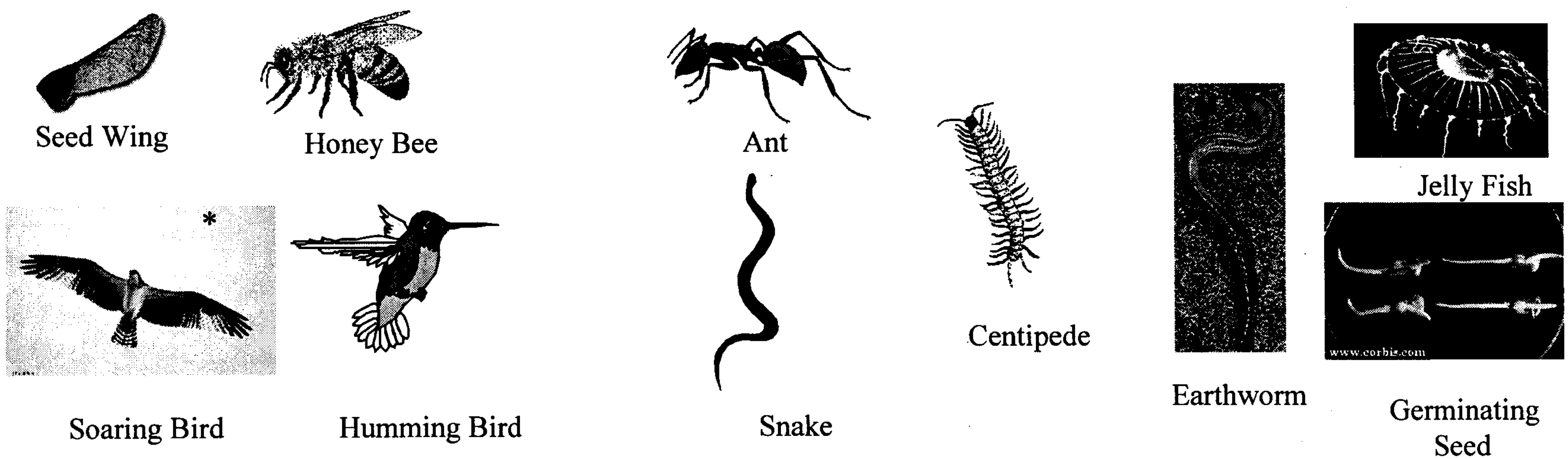
# Biomorphic Explorers: Classification
# (Based on Mobility, Ambient Environment)

**Biomorphic Explorers**

- **Aerial**
  - **Biomorphic Flight Systems**
- **Surface/Subsurface**
  - **Biomorphic Surface Systems**
  - **Biomorphic Subsurface Systems**




**Examples of biological systems that serve as inspiration for designing the biomorphic explorers in each of these respective classes**

*http://www.gregscott.com/rwscott/rwscott.htm

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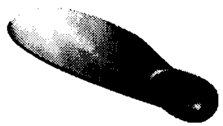
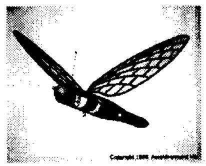
# Biomorphic Explorers: Classification
# (Based on Mobility/Ambient/Environment)

## Biomorphic Explorers

### Aerial

**Biomorphic Flight Systems**

Ornithopter

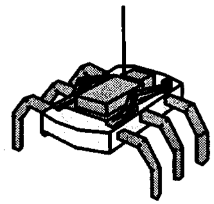
Seed Wing Flyer (60 g)


Glider (75 g)

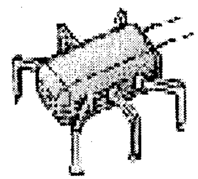
Powered flyer

### Surface/Subsurface

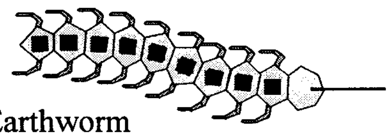
**Biomorphic Surface Systems**



Hexapod
(2 ~~Kilogram~~)

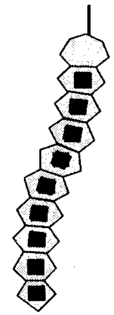


Reconfigurable Legs/Feet

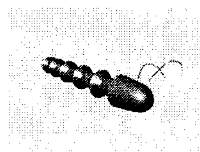


Earthworm

**Biomorphic Subsurface Systems**




Artificial Jelly Fish



Animated Model of a Burrowing Robot

**Candidate biomorphic explorers on the drawing board, with ~~in~~ parentheses ~~showing~~ mass of design under study in 1998 in ~~each of~~ these respective classes**

*http://www.gregscott.com/rwscott/rwscott.htm

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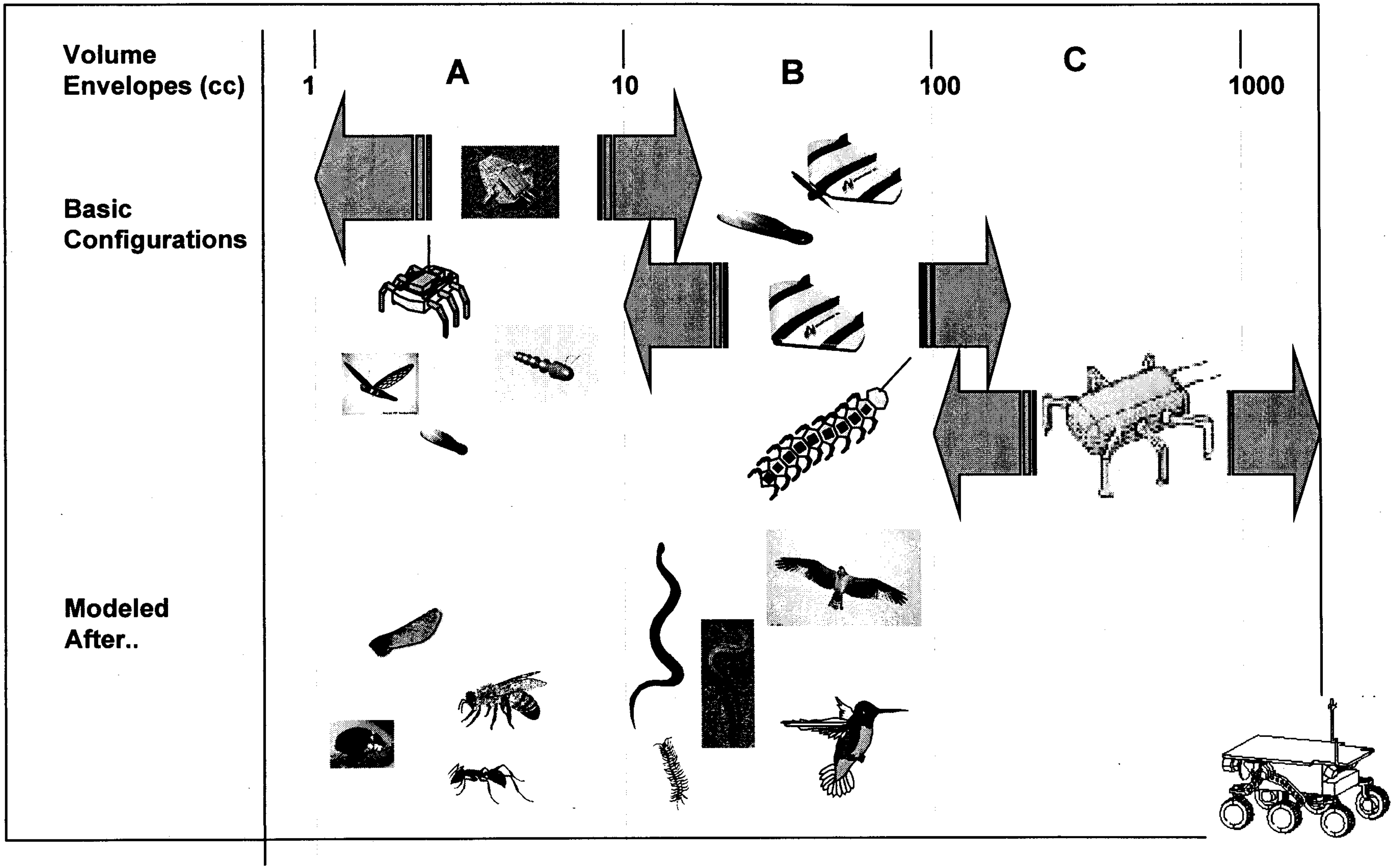
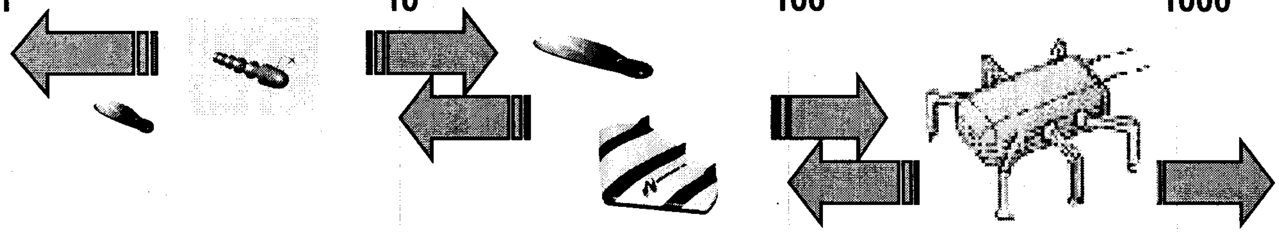
# *MICROEXPLORERS: BASIC CANDIDATE CONFIGURATIONS*



# *MICROEXPLORERS: BASIC CANDIDATE CONFIGURATIONS*

| Volume Envelopes (cc) | 1 — **A** — 10 | 10 — **B** — 100 | 100 — **C** — 1000 |
|---|---|---|---|
| Basic Configurations |  | | |
| Description: | • ~1 to 20 ~~cc~~ cm³ volume envelope<br>• ~0.2 to 5 g mass<br>• 6 or 8 legs, like an ant, lady bug or a spider; fixed structure. | • ~10 to 200 ~~cc~~ cm³ volume envelope<br>• ~2 to 50 g mass<br>• Direct-driven, legged or muscular-limb-based mobility mechanism; multiple legs/limbs, segmented, modular body, like a snake or centipede. Could be concatenated version of Category A | • ~100 to 2000 ~~cc~~ cm³ volume envelope<br>• ~20 to 500 g mass<br>• Direct-driven, legged (or conventional wheeled) mobility mechanism<br>• This size is closer to a small ~~animal~~ than a large insect. |
| Sensors: | • Single "needle" sensor and single antenna for telecom | • Multiple needle sensors and antennae for sensing the local environment, or may include micro-imagers | • Sensors may include miniaturized camera, optical micro-machined spectro-meters, dedicated chemical sensors |

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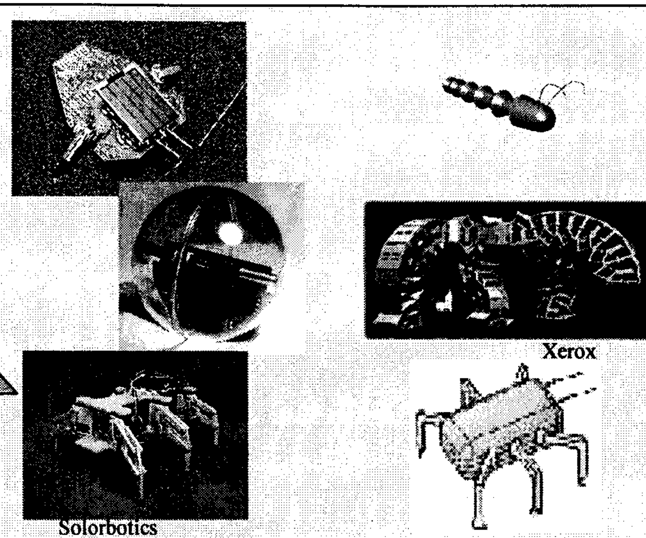
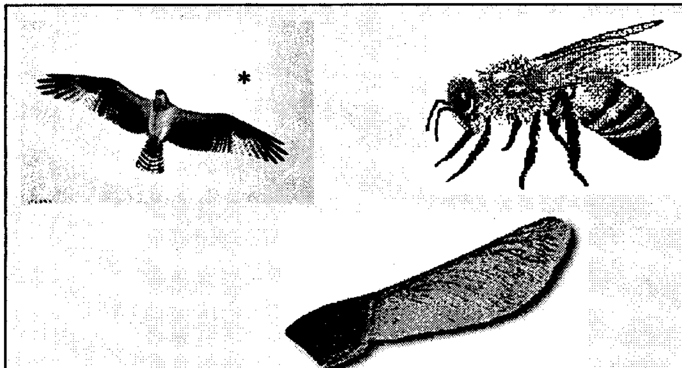
# BIOMORPHIC EXPLORERS: VERSATILE MOBILITY

BIOLOGICAL EXAMPLE OF RECONFIGURABLE MOBILE UNIT

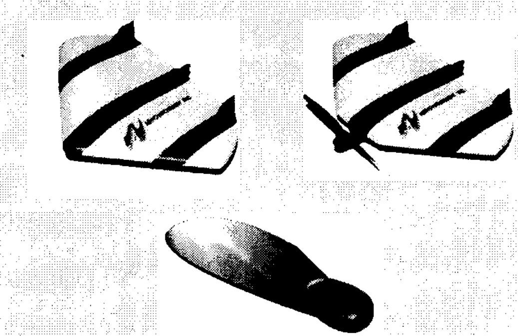



CHALLENGE: TO DESIGN RECONFIGURABLE MOBILE UNIT

SURFACE/ SUBSURFACE




BIOLOGICAL EXAMPLES OF FLYERS



BIOMORPHIC FLIGHT SYSTEMS
• DOD LEVERAGE

FLYERS

*http://www.gregscott.com/rwscott/rwscott.htm

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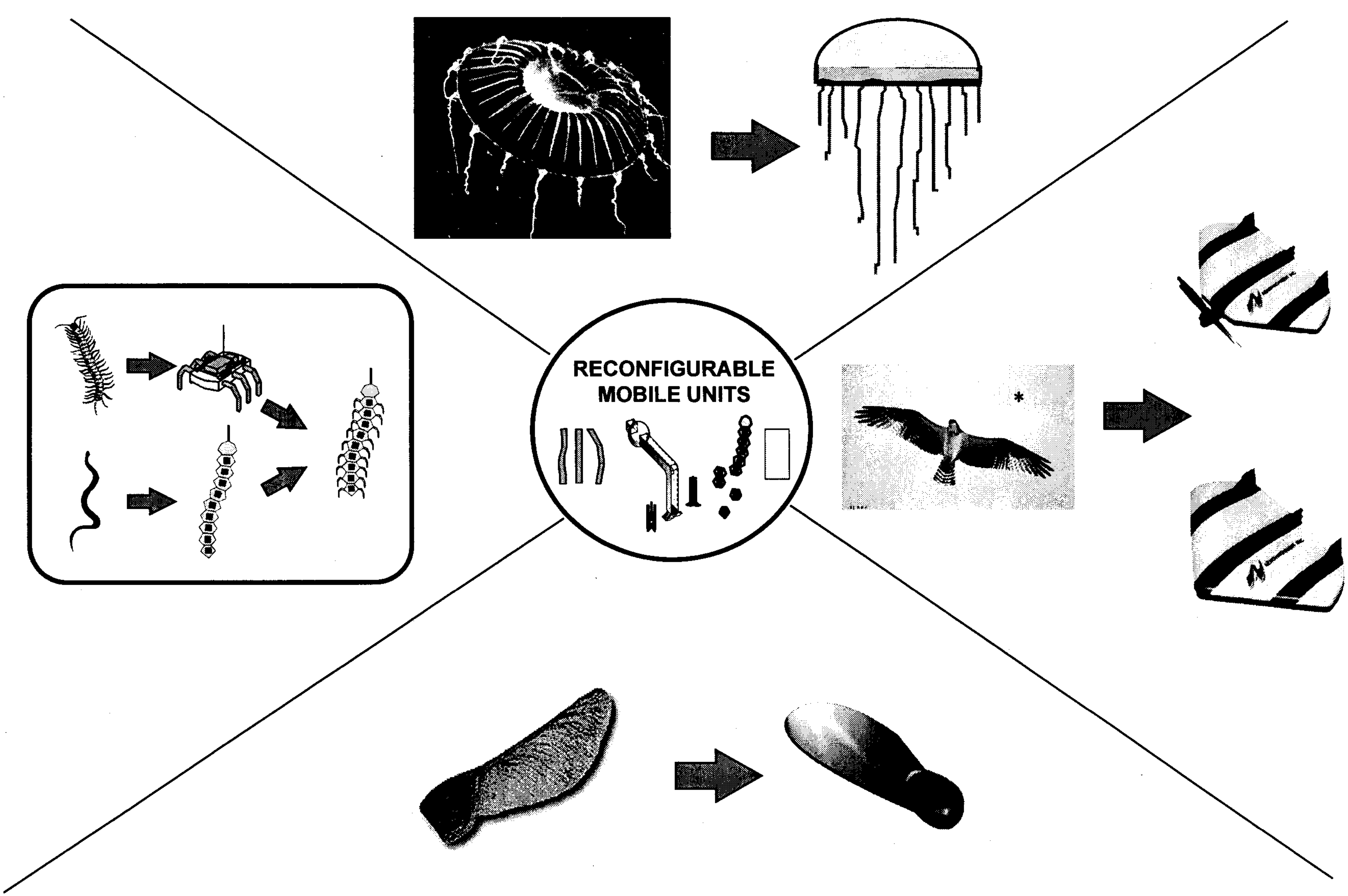
# *ADVANCED MOBILITY FOR BIO-MORPHIC EXPLORERS*




*http://www.gregscott.com/rwscott/rwscott.htm

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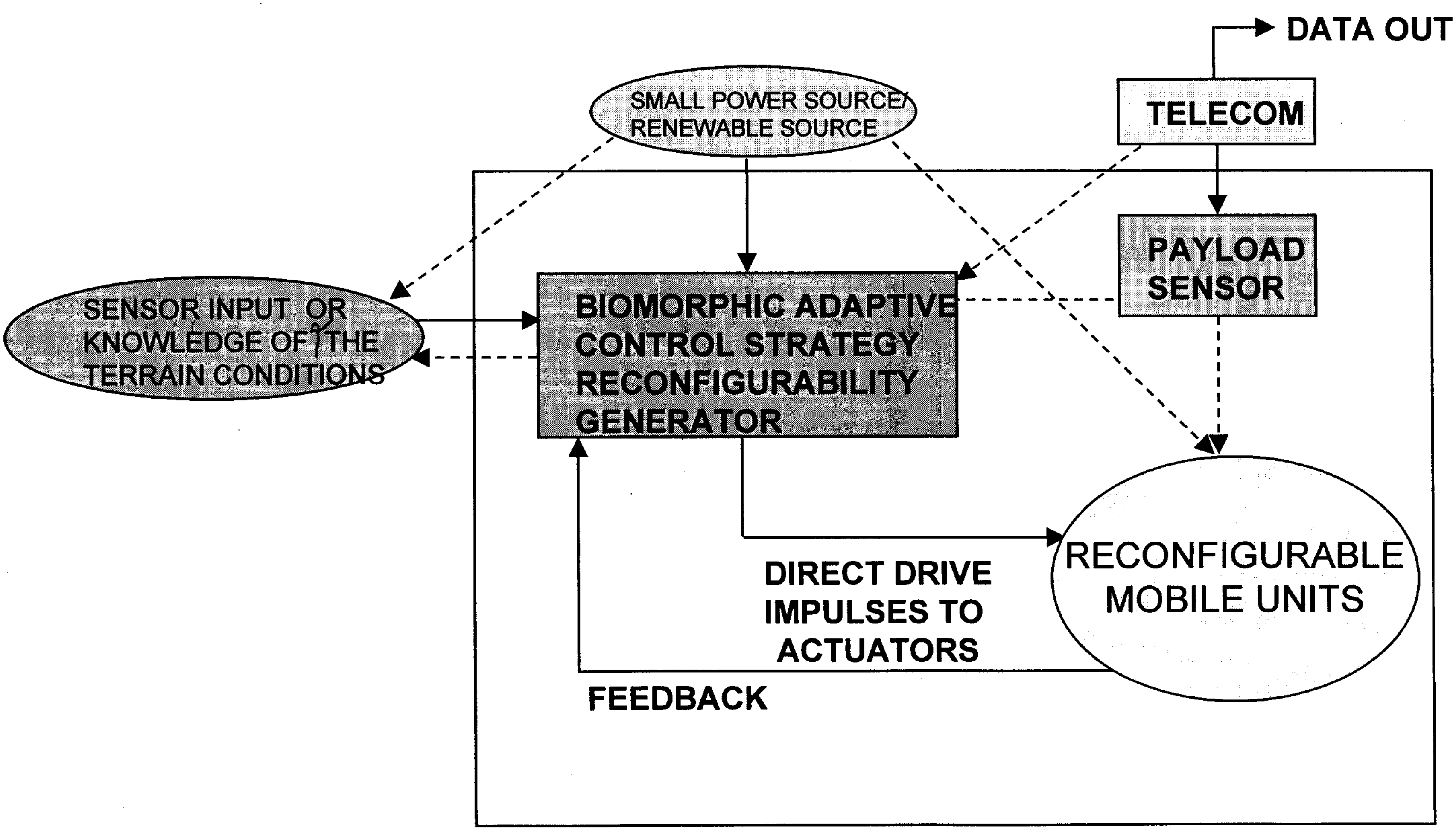
# Distributed control Operational Schematic



# Distributed control Operational Schematic

EXPLORER
(OBJECT OF CONTROL)
INCL. SENSORS, ACTUATORS

+

EXPLORATION OR
EXPERIMENTAL
SCENARIO

MOTION/MOBILITY GOAL

- IDENTIFY DESIRED MOTION SEQUENCES TO ACCOMPLISH GOAL

SENSOR → ACTUATOR
MAPPING

- CONTINUOUS
- MULTIDIMENSIONAL
- COMPLEX

IMPLEMENTATION IN NN CHIP

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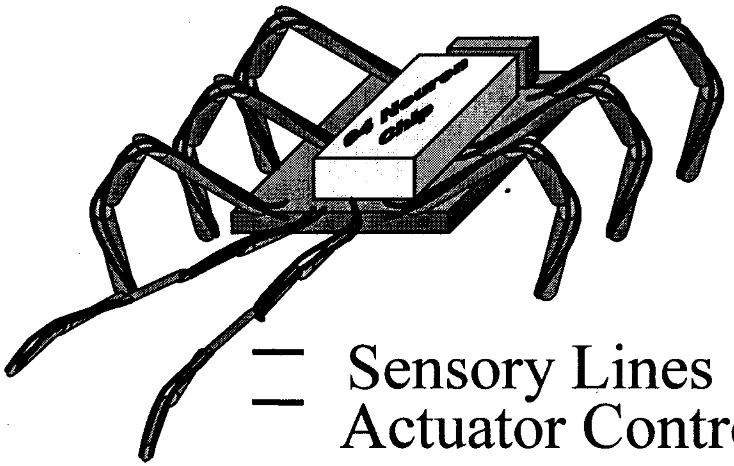
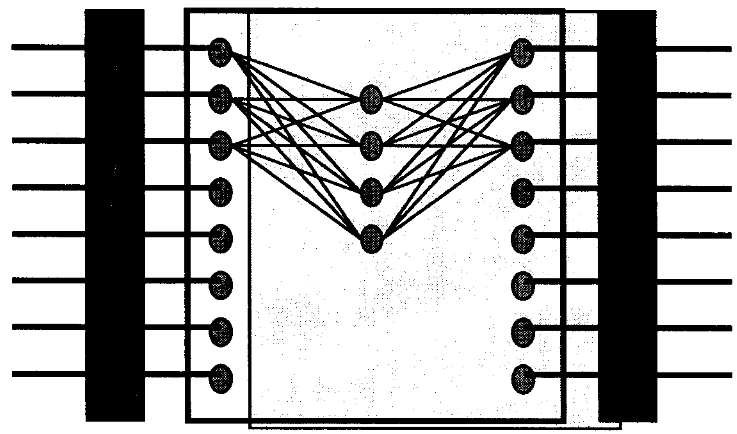
## Neurally-controlled Biomorphic Explorer

## Neural connections mapped on 64 Neural Network (NN) Chip




Sensory Lines
Actuator Controls



JPL's 64 NN chip Characteristics:

- Low Weight (5g)
- Small Size (1cm x 1cm)
- Low Power (12mW)
- High Speed (~250nsec)
- Programmable Neural Network Architecture

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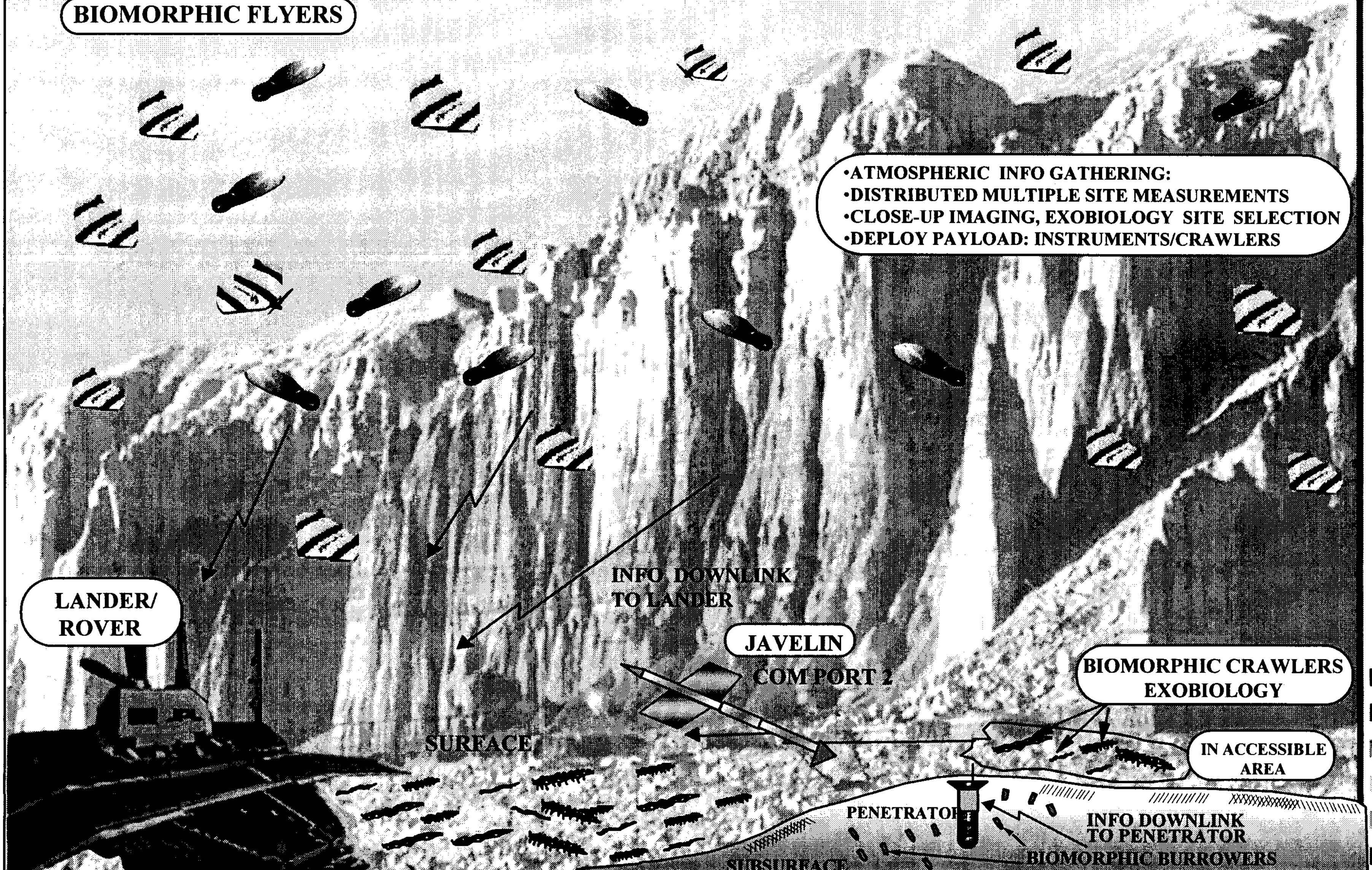
# CO-ORDINATED/CO-OPERATIVE EXPLORATION SCENARIO




CO-OPERATIVE ORGANIZATION OF LANDER, ROVER, AND A MULTITUDE OF A VARIETY OF INEXPENSIVE BIOMORPHIC EXPLORERS WOULD ALLOW COMPREHENSIVE EXPLORATION AT A LOWER COST WITH A BROADER COVERAGE

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# BIO-MORPHIC EXPLORERS

- **PAYOFF**

- **BIOMORPHIC EXPLORERS IN COOPERATION WITH CURRENT EXPLORATION PLATFORMS SUCH AS LANDERS AND ORBITERS CAN ENABLE**
  - **EXPLORATION OF CURRENTLY INACCESSIBLE LOCATIONS**
  - **MUCH BROADER COVERAGE OF EXPLORATION SITES**
  - **EXPLORATION AT LOWER COST**

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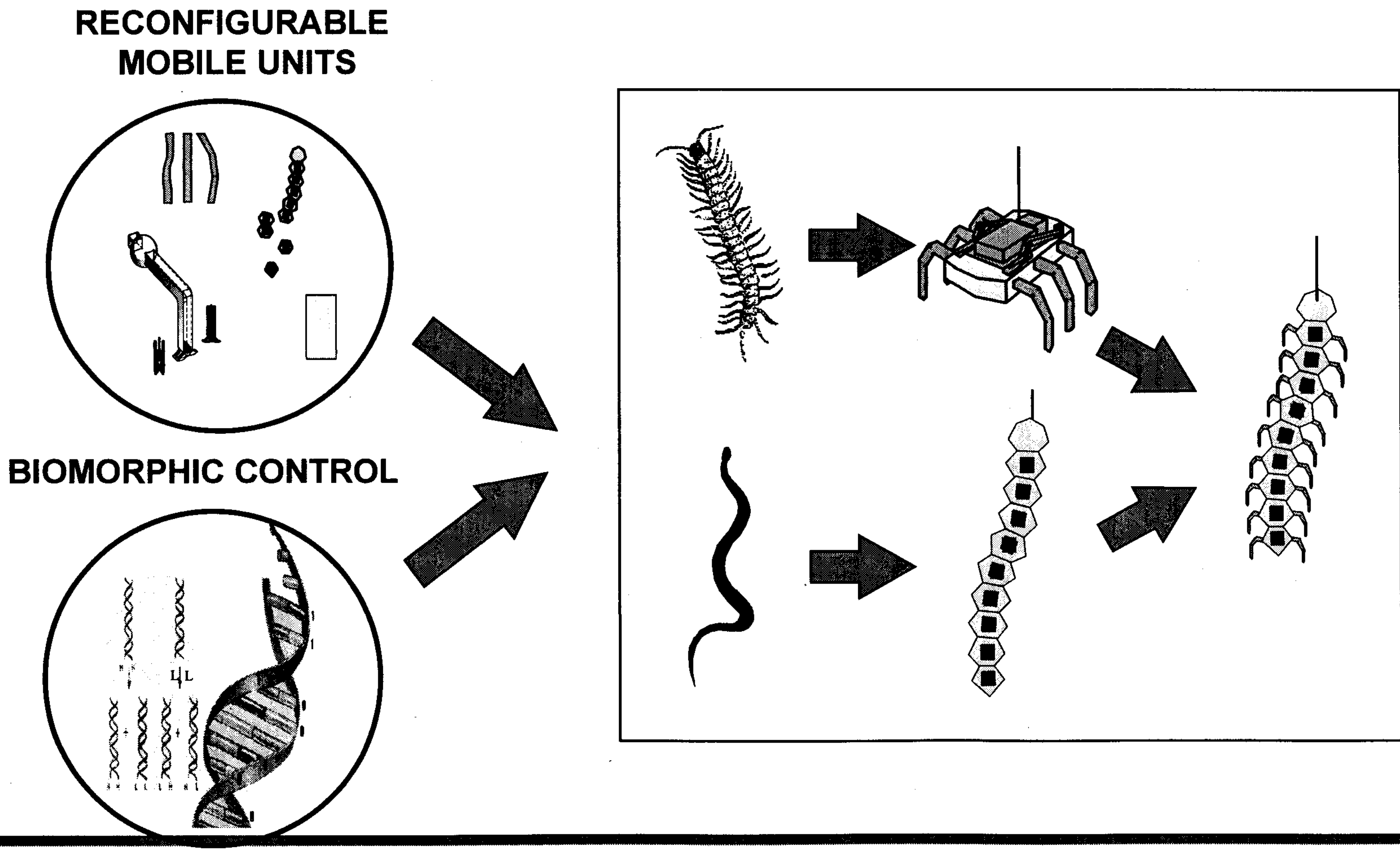
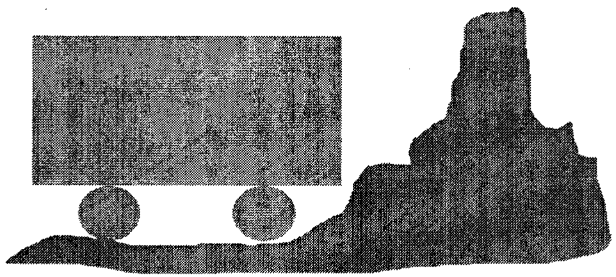
# BIO-MORPHIC SURFACE SYSTEMS

- **BIO-MORPHIC SURFACE SYSTEMS ARE A UNIQUE COMBINATION OF RECONFIGURABLE MOBILE UNITS and THEIR CONTROL BY ADAPTIVE, FAULT TOLERANT ALGORITHMS TO AUTONOMOUSLY MATCH WITH THE CHANGING AMBIENT/TERRAIN CONDITIONS. THEY PERFORM IN COOPERATIVE MODES TO ENABLE SCIENCE RETURN CURRENTLY INACCESSIBLE**

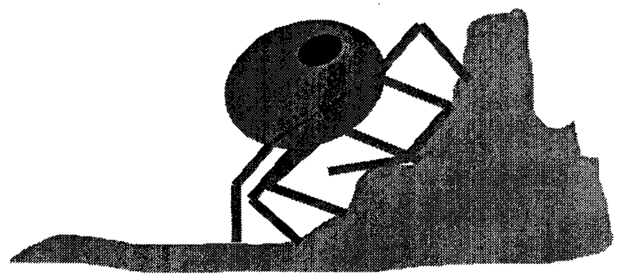


# *MOTIVATION: PARADIGM SHIFT FOR ENHANCED SCIENCE RETURN*

**CURRENT ROVERS**



**BIOMORPHIC MICROEXPLORERS**



TRADITIONAL ACTUATORS/MOTORS → FLEXIBLE, RECONFIGURABLE MOBILE BUILDING BLOCKS

CONVENTIONAL CONTROL → HYBRID DIGITAL-ANALOG NEURAL CONTROL

CONVENTIONAL DESIGN → EVOLVED FOR ADAPTATION, RECONFIGURABLE

INDIVIDUALISTIC BEHAVIOR → COOPERATIVE BEHAVIOR

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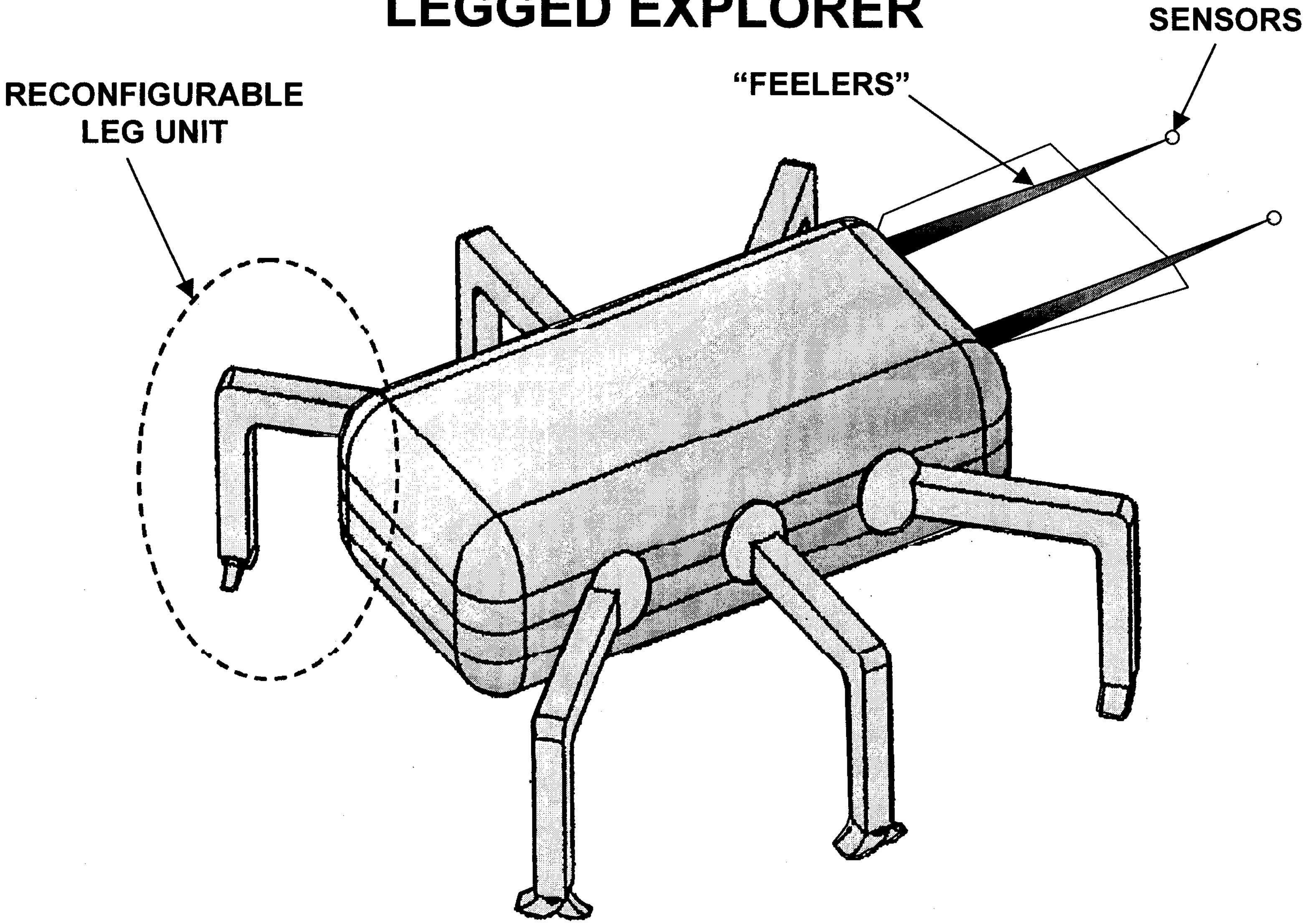
# MULTITERRAIN RECONFIGURABLE LEGGED EXPLORER

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### *Overview of Six-Legged Explorer*

**The explorer shown on previous page is designed* for multi- terrain traverse. It utilizes six legs, each of which have two rotational degrees of freedom at a shoulder ball-pivot. The rotations at the shoulder result in net translation of the feet. In this way, the robot can be made to both step forward and up. To augment the capabilities of the explorer, the mobility system can be reconfigurable, either by changing its footprint or by changing the overall length of the leg, or both. The actuation is based on sets of SMA wires and cantilever springs. An individual set consists of a wire and a spring attached to the end of the leg lever arm in linear apposition. Two orthogonal sets comprise one actuation cell, capable of moving a leg with two degrees of freedom. In the case of a vertical set, the spring is designed to support the weight of the explorer, while the SMA need only stretch the spring. This reduces the necessary maximum force rating of the SMA. A lower maximum force rating implies a smaller diameter wire, which requires less power and has a faster cycle time. Preliminary estimates indicate that a 37 m SMA wire would suffice for the force and power required to obtain this mechanism. A refinement of the actuation would place several wires in series, for each set, this arrangement would allow for variable step size (steering).**

### *Reconfigurable Foot Overview*

**The reconfigurable foot** (next page, figure 'a' and 'b') **is intended to provide a good grip on a range of substrates from hard and rocky to soft and sandy respectively. This effect is achieved through a variable footprint design. For a hard matrix, the scissor-like foot is retracted into the leg via the contraction of a SMA wire. This presents a footprint that is primarily composed of the leading edges of the foot pads. For a soft matrix, the SMA is relaxed, and the torsional spring wrapped around the foot axle pulls the foot out the leg housing and spreads the foot pads to their greatest extent. The footprint in this case is the full flats of the foot pads.**

### *Reconfigurable Leg Overview*

**The reconfigurable leg** (next page, figure 'c' and 'd') **would be a way to have a robot that was capable of relatively high ground force as well as relatively high ground speed, though not at the same time. In essence, it simply is a telescopic leg, the extension and retraction of which is governed by an appositional set of SMA wire and tension spring. Whether the SMA actuates the extension or retraction is arbitrary. If the extension of the leg is perpendicular to the direction of the leg travel (and net actuation force), the load on the actuator will go down with the percentage decrease in effective leg length, and the step size will increase with the percentage increase in effective leg length. In other words, the load on the actuators can be decreased in situations such as going up hill and lifting the robot over obstacles by shortening the leg, and the speed can be increased over flat ground by lengthening the legs.**

* "Biomorphic Multi-Terrain Robots for Earth or Outer Planets Exploration", New Technology Report, Dec 1997, NPO# 20381/9978.

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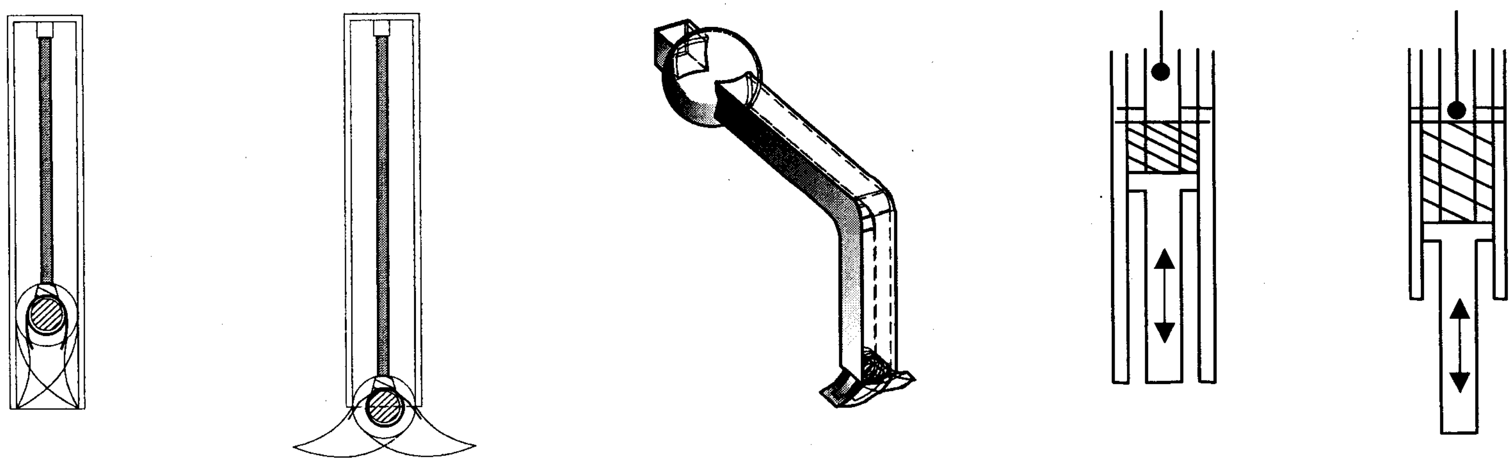
# RECONFIGURABLE FOOT/LEG OF BIOMORPHIC EXPLORER



SHORT FOOTPRINT — 'a'

WIDE FOOTPRINT — 'b'

SHORT LEG — 'c'

LONG LEG — 'd'

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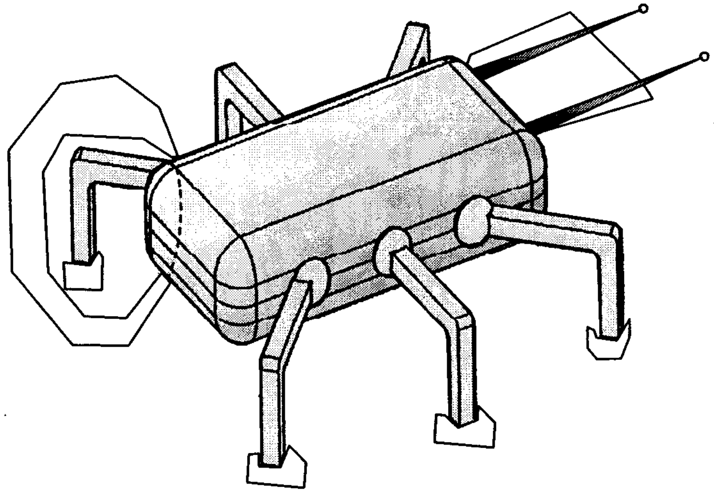
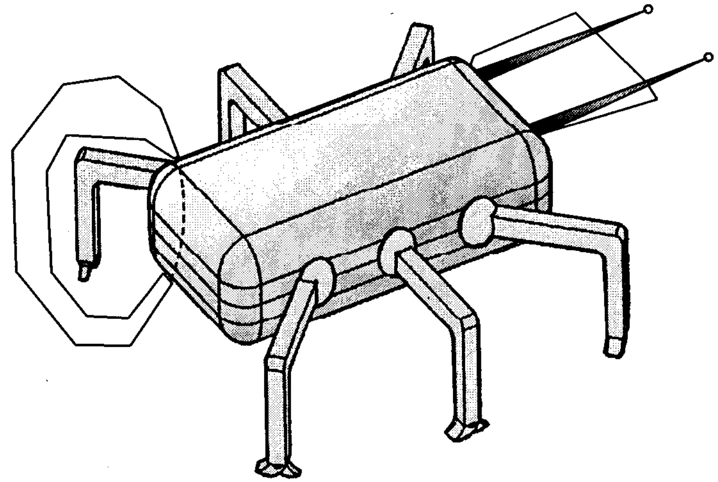
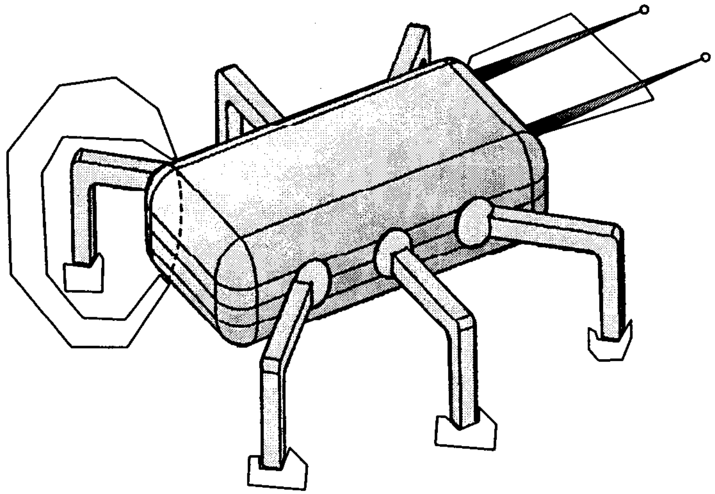
# MULTITERRAIN RECONFIGURABLE LEGGED EXPLORER



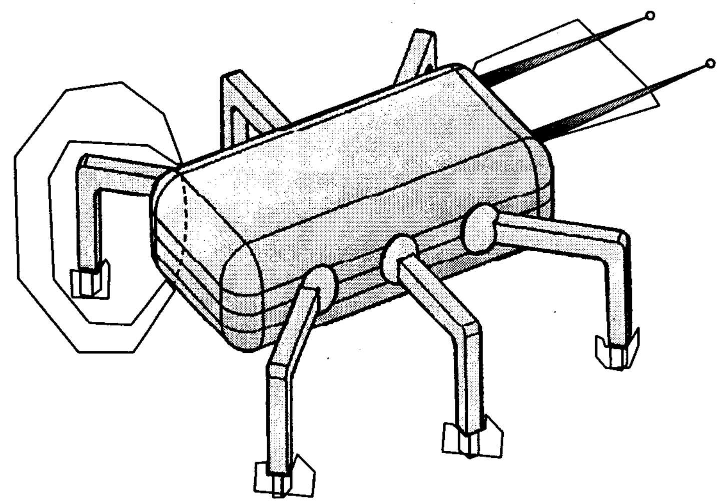
SHORT FOOTPRINT



WIDE FOOTPRINT



SHORT LEG



LONG LEG

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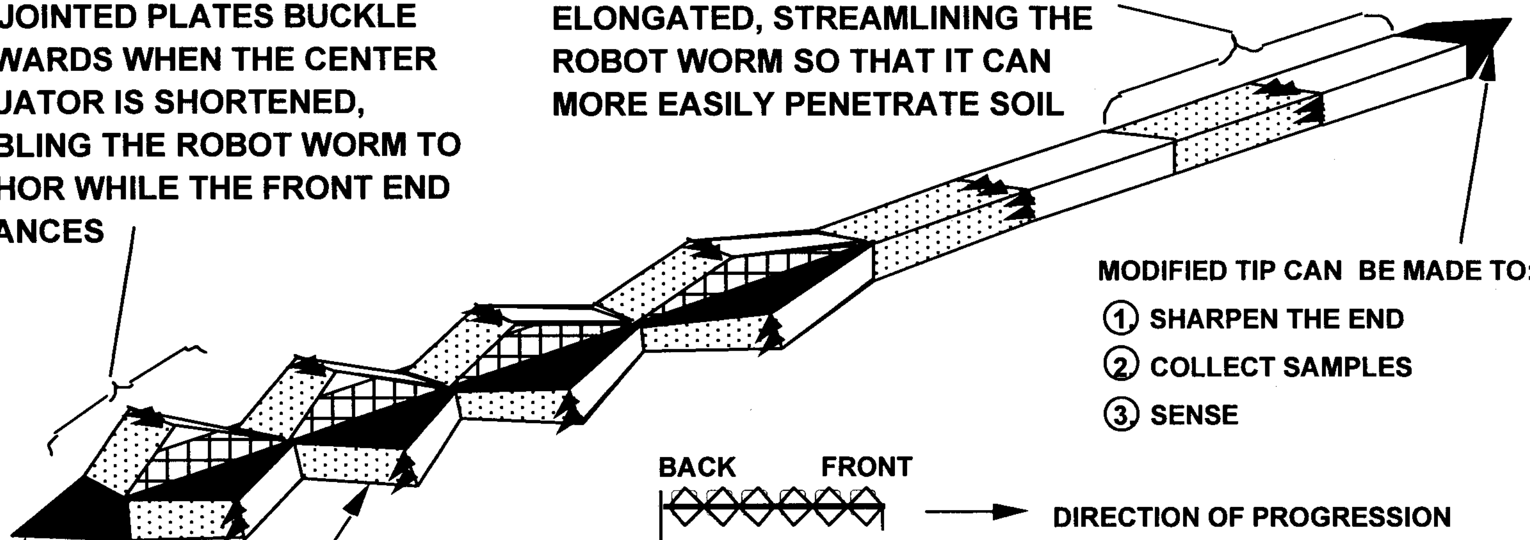
# EARTHWORM LIKE BURROWING ROBOT

THE JOINTED PLATES BUCKLE OUTWARDS WHEN THE CENTER ACTUATOR IS SHORTENED, ENABLING THE ROBOT WORM TO ANCHOR WHILE THE FRONT END ADVANCES

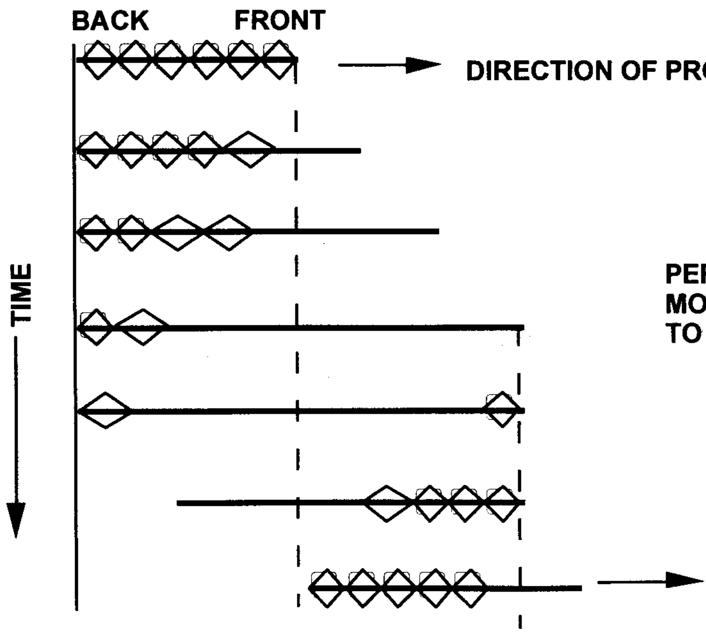
THE JOINTED PLATES LAY FLAT WHEN THE CENTER ACTUATOR IS ELONGATED, STREAMLINING THE ROBOT WORM SO THAT IT CAN MORE EASILY PENETRATE SOIL



MODIFIED TIP CAN BE MADE TO:

1. SHARPEN THE END
2. COLLECT SAMPLES
3. SENSE

LITTLE SPIKES ON THE PLATES PROVIDE FURTHER TRACTION ONLY WHEN THE PLATES ARE IN THE BUCKLED POSITION




PERISTALSIS-LIKE MOTION SIMILAR TO EARTHWORMS

MOTION COULD BE MADE BI-DIRECTIONAL BY CHANGING SEQUENCE OF SEGMENT SHORTENING AND ELONGATION BY ACTUATORS

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The previous page illustrates an **earthworm like robot** capturing the peristalsis mechanism for mobility. An application specific design of such a robot could offer a good solution for tunnelling/ crawling into cracks in rocks or under rock surfaces. Dedicated sensors such as a miniature active pixel sensor (APS) camera, temperature sensor, or life sensor will form the payload of such an explorer to obtain distributed measurements for scouting the site of interest. Life sensing can be done by looking for carbonates, water, etc. The front and end segments of the earthworm robot will always perform themobility function whereas the center segments would 'hold' the payload as needed.

Novel features of the earthworm robot as described elsewhere* are:

- Segmented foldable design
- Fault-tolerance, adaptibility
- Flexibility allowing enhanced spatial access
- Reconfigurability allowing adaptibility to terrain
- Enhanced spatial access
- Enhanced sample acquisition
- Scaleability
- Reduced complexity/cost
- Surface/subsurface mobility

*S. Thakoor and B. Kennedy; "Biomorphic Systems based on Smart Actuators", Proc. of SPIE, Vol. 3326, Smart Structures and Materials 1998, Pg. 308-322, Mar 1998.
."Earthworm Robot Implementation of Biomorphic Explorers- Folding Mechanisms and flexible Multipods", New Technology Report, April 1997, NPO# 20266/9880.

## Reptile-Like Flexible Explorer

Taking inspiration from the burrowing techniques of *Amphisbaenia* (as presented by Gans*), a design for a subterranean reptile-like flexible penetrator has been created and has been described ealier[32]. The *Amphisbaenia,* a generally leg-less order of reptiles, create tunnels by forcing themselves through the soil. More specifically, they impact the head of the tunnel with their own heads, then compact the soil into the walls of the tunnel. Different species accomplish these actions in different but similar ways. In general, annular rings along the body are expanded against the tunnel's wall, anchoring the animal. A rectilinear motion is then created, culminating in the head striking the head of the tunnel. Once the snout is wedged within the soil, the head is moved back and forth or up and down (keel- or spade-headed species, respectively). This motion compacts the soil in the walls and opens the tunnel so that the animal can move forward. The process is then repeated. The *Amphisbaenia* are a successful order of reptiles that move through the soil in a manner and with an efficiency that conventional mechanical systems cannot. If a rover were created that could mimic the majority of their movement modes, that rover should be able to burrow with an efficiency approaching that of the reptiles.

**Overview of the mechanism:**

To emulate the behavior of these reptiles requires a mobility system capable of two distinct motions: anchored rectilinear motion and transverse movement of the head and body. The accompanying schematic (figure 8) shows a design composed of a series of modules capable of creating these motions. The anchored rectilinear motion is provided by the modules that look like two cones placed base to base. Within these cones is a piston-like assembly, actuated by sets of spring-opposed SMA wires and/or other linear actuators. When the piston is actuated, the outer cone is expanded, providing an anchor in the tunnel walls. Meanwhile, the module's length is decreased. The sketch shows the two rear modules in anchor mode and the three forward modules in extended mode. If the body is anchored by other modules, the release of a particular piston results in the net forward motion of the corresponding module.

**Special Issues in the Implementation of this Mobility System**

Gans' work provides a blueprint for mobility. In general, the movement will proceed as described above with the gradual lengthening and widening of a tunnel. A troublesome case, however, is the initial entry into the soil. The simplest solution is to burrow into the side of a hill. In this case, the method is the same as for normal burrowing, except the anchor modules can only use the surface soil for resistance. It may be necessary to first dig a starter hole by moving the head into a position normal to the surface by arching the appropriate collars, then pivoting the head about the point of the snout. This movement will eventually displace enough soil that a more normal mode of movement may be used

**Design Refinements**

•To decrease frictional losses, all cone surfaces that are directly loaded by the soil should be covered by some Teflon-like coating.
•Depending on the soil conditions and mobility requirements, different head designs could be used. (I.e., a spade-head might be more useful for deep-burrowing rovers as opposed to a keel-head, which might be more useful for in-the-plane steering.

*C. Gans , Proceedings International Symposium on Vertebrate Morphology. Stuttgart and New York: Gustav Fischer Verlag, pp.13-22 (1985); Jayne, B.C. J. Morphology. 197. pp. 159 - 181(1988); J. P. Ostrowski and J. W. Burdick, Int. Conf. on Robotics and Automation (1996).

# Aqua Worm Variation for Europa Subsurface Ocean Exploration

A possible design variation that relies primarily on the peristaltic component of motion would be an amphibious worm. Since the general form of locomotion for a peristaltic worm treats soil as a highly viscous liquid, the design could be refined to optimize motion through less viscous fluids such as water. The primary difference would be the inclusion of louvers in the front cone of the anchor modules. These louvers would act as one-way valves through which water could pass as the module moves forward, but which would resist backward motion as the module came into the anchored position. These louvers could either be passive, using the force of the water to close them, or active. Moreover, the front cones themselves would have to be lengthened, providing a larger surface area when in the anchored position. Several other design issues would have to be explored, as well, including the streamlining of the head and modules for hydrodynamic efficiency and the development of a buoyancy system. Such a amphibious worm robot will have clear applications for exploration of subsurface oceans on Europa.

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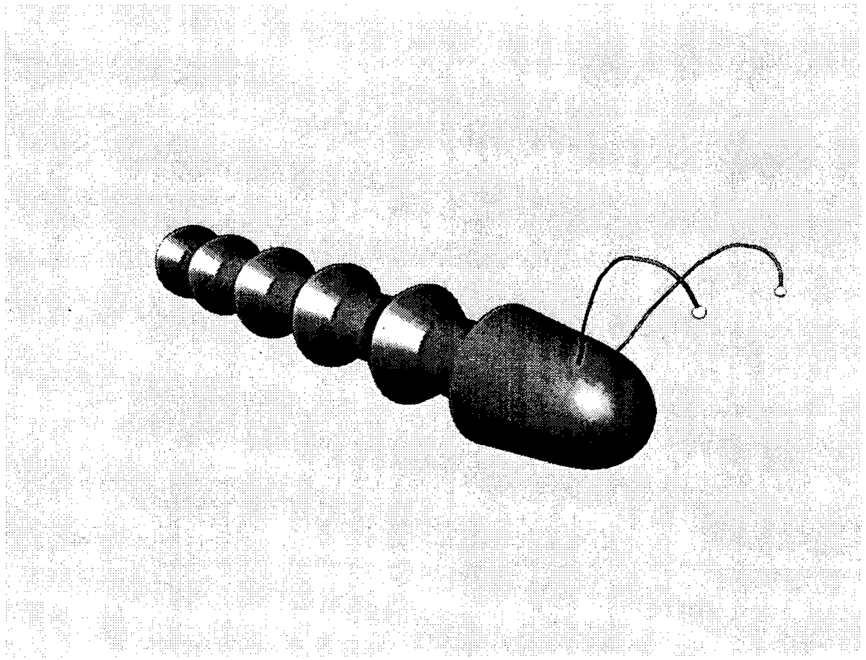
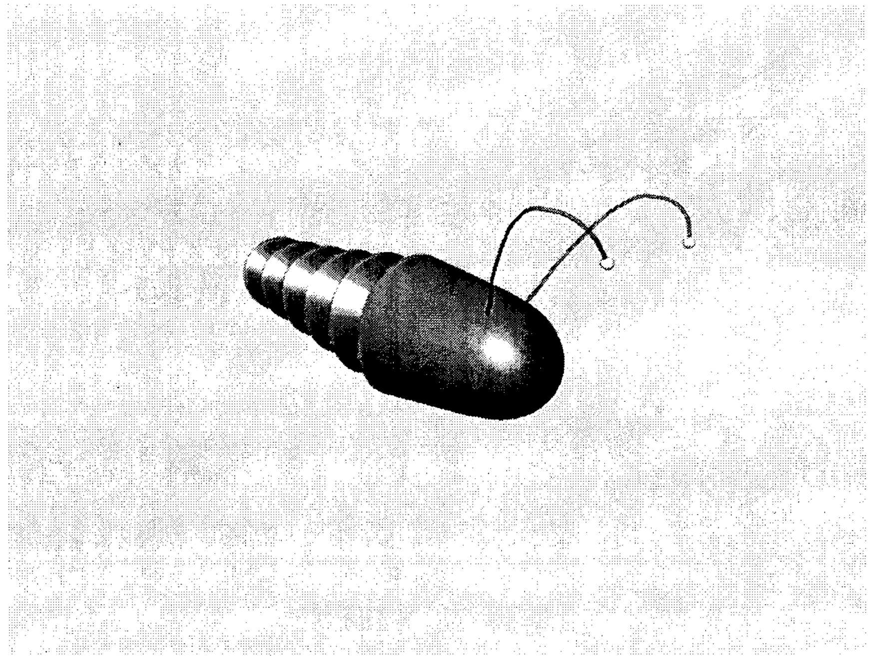
# WORM ROBOT FOR IN-SITU EXPLORATION



EXTENDED CONFIGURATION



CONTRACTED CONFIGURATION

***Z. Gorjian and S. Thakoor, "Biomorphic Explorers Animation Video", 1st NASA/JPL WORKSHOP ON BIOMORPHIC EXPLORERS FOR FUTURE MISSIONS, August 19-20, 1998; Jet Propulsion Laboratory, Pasadena, CA**

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# Biomorphic Flight Systems: Vision

- Extended reach over all kinds of terrains
- Unique perspective for imaging
- Many flyers work in cooperation with orbiters, landers, larger aircraft and balloons to enable new mission to reach currently inaccessible locations

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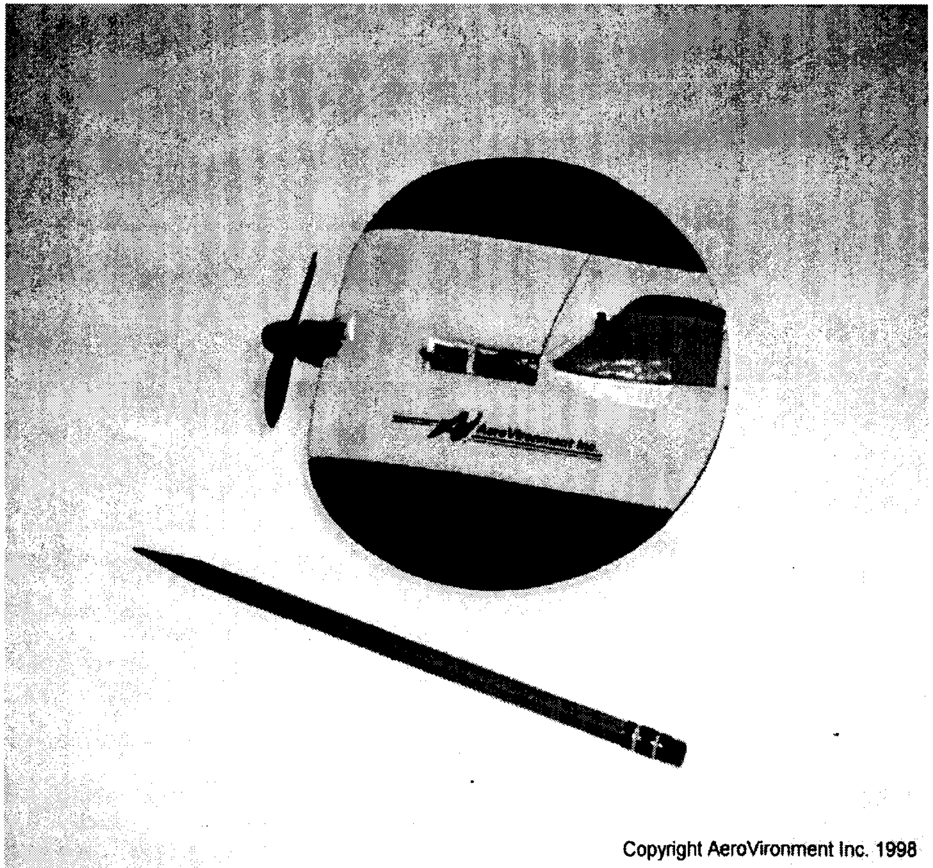
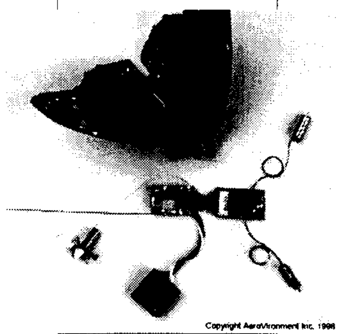
# Micro Air Vehicles: Current Status

- Micro Air Vehicles (MAV) are currently being developed under a DARPA program for terrestrial applications with similar motivations to potential Mars exploration objectives.



Copyright AeroVironment Inc. 1998

- **Total Mass = 43 gm**
  - 27 gm Li battery
  - 7 gm DC motor
  - 1 gm propeller
  - 2 gm heatsink
  - 4 gm airframe
  - 1 gm servos
  - 1 gm FCC & Comm
- **Wing Span = 15 cm**
- **Duration = 960 sec**
- **Velocity = 17 m/s**



- Flight Control Computer
- Servo Actuators
- Motor Control
- Airspeed Sensor
- Communications

- MAV built by AeroVironment

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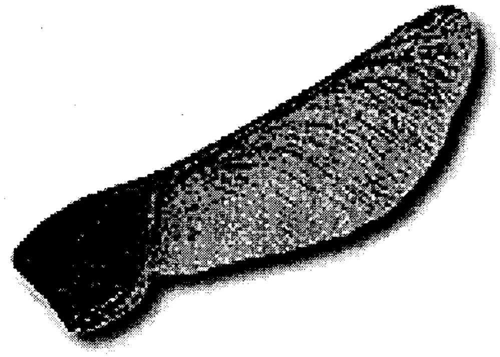
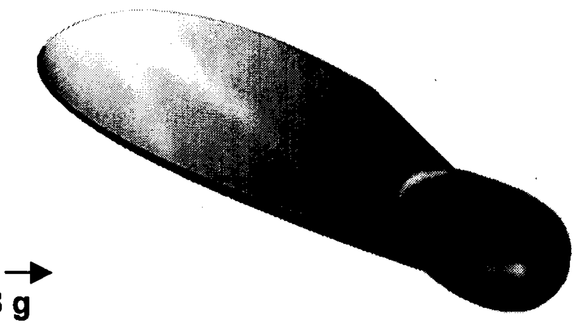
# BIOMORPHIC FLIGHT SYSTEMS
# JPL-AEROVIRONMENT COLLABORATION

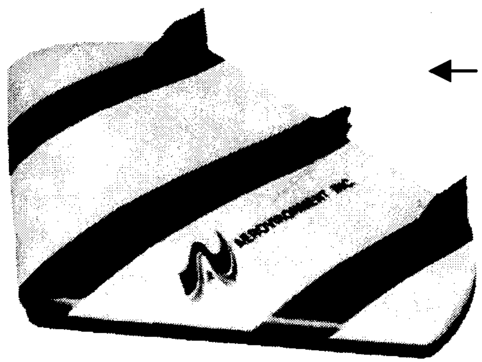


a. Seed Wing Pod

TOTAL MASS: 57 g
PAYLOAD MASS: 48 g



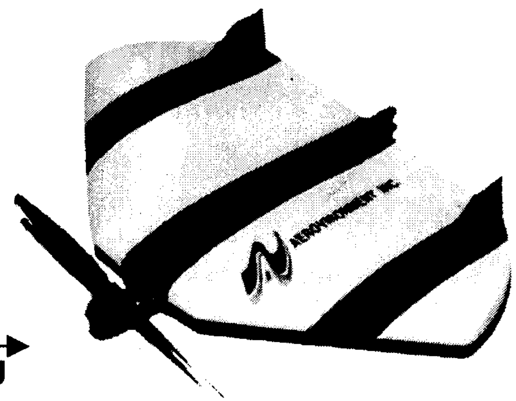
b. Seed Wing Pod Flyer



TOTAL MASS: 57 g
PAYLOAD MASS: 32 g

c. Biomorphic Glider

TOTAL MASS: 57 g
PAYLOAD MASS: 6 g



d. Biomorphic Flyer

Biomorphic Flight Systems offer rapid mobility and extended reach

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# Biomorphic Gliders

- **Small, simple and low cost system ideal for reconnaissance and wide area dispersion of sensors and small experiments.**
- **Payload mass fraction higher (50-70%) compared to powered flyers.**

**Design Goals:**

•Small total mass, ~100 grams
•High payload mass fraction, >50%
•Mobility: L/D ~5, controlled flight, autonomous navigation using sun position
•Captures features of soaring birds, utilizing rising currents in the environment

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# Biomorphic Glider Mission Concept

- **Mission Objective**
  - Up-close, high resolution imagery of targeted sites.
  - In situ surface chemical / mineralogical measurement to augment imagery.
  - Atmospheric survey.
  - Reconnaissance for lander / rover mission planning (site selection).
- **Deployment**
  - Airborne platforms (balloons, larger aircraft)
  - Space (entry probe)
- **Payloads**
  - MEMS chem, soil oxidation, or pH
  - Temperature and pressure
  - Imaging camera
  - IR sensor
- **Flight Profile**
  - The deployment platform carries several gliders. Gliders are released after identifying a target site and specifying a flight heading, or they fly a pre-programmed flight trajectory (based on sun angle).
  - The gliders fly to the surface collecting atmospheric properties (temperature and pressure) and imagery.
  - After landing, each glider conducts a surface experiment which is analyzed using a MEMS sensor for presence of key trace elements or soil properties.
  - The glider then transmits the data to the deployment platform or other relay.

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# μFlyers - Powered Vehicle

- Payload mass fraction 10 to 20%.
- Scaling: Span ~ Mass^0.5
- Trade-off between payload mass and range.
- Launch from landers, rovers, entry probes, or larger aircraft.
- Reconnaissance and small sensor / experiment dispersion


## Representative Design parameters:

- Total Mass = 57 gm
- Payload Mass = 6 gm
- Wing Span = 0.194 m
- Wing Area = 0.019 m^2
- Volume = 380 cm^3
- Flight Speed = 84 m/s
- Range = 10 km
- Duration = 120 sec
- Glide Ratio = 5.3
- Starting Alt. = 0 km

- Performance calculations based on conditions at 5km altitude.

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# Powered Mission Concept

- **Mission Objective**
  - Imagery of over-the-horizon terrain and in situ surface chemical / mineralogical measurement for rover mission planning (site selection).
- **Deployment**
  - Lander
- **Payloads**
  - MEMS chem, soil oxidation, or pH
  - Temperature and pressure
  - Imaging camera
  - IR sensor
- **Flight Profile**
  - The rover is equipped with several μFlyers. A mechanical spring is used to launch the μFlyer after specifying a flight heading (sun angle).
  - The μFlyer relays imagery to the lander.
  - After landing, each glider conducts a surface experiment which is analyzed using a MEMS sensor for presence of key trace elements.
  - The μFlyer, equipped with a small solar cell, then acts as a radio beacon for rover navigation.
  - The rover can also be equipped with μFlyers to help find suitable pathways.

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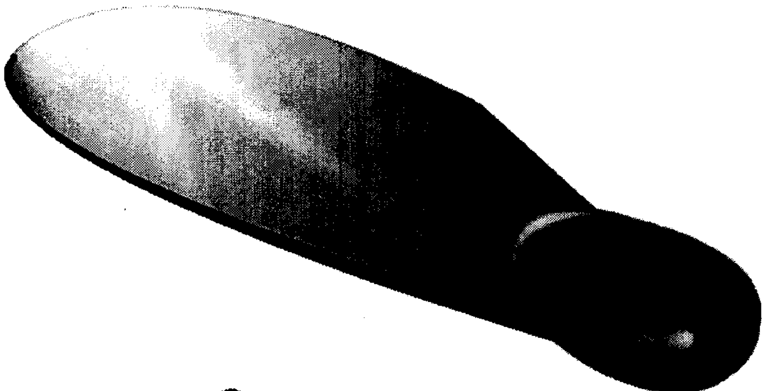
# Seedwing Flyers

- **Simpler and smaller than parachute on small scale for dispersion of sensors and small experiments.**
- **Payload mass fraction >80% possible.**



Maple seed

**Design Goals:**

•Small total mass, ~100 grams
•High payload mass fraction, >80%
•Captures key features of slow and stable descent as observed in the plant seeds such as Samaras, Maple Seed

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# Seedwing Mission Concept

- **Mission Objective**
  - Wide area dispersion of in situ surface chemical / mineralogical measurement to augment imagery.
  - Atmospheric survey.
  - Reconnaissance for lander / rover mission planning (site selection).
- **Deployment**
  - Entry probe or airborne platform (glider, balloon, powered a/c)
- **Payloads**
  - MEMS chem, soil oxidation, or pH
  - Temperature and pressure
- **Flight Profile**
  - Seedwings are sequentially deployed from another airborne platform (glider, balloon) or entry probe.
  - Each seedwing autorotates to the surface collecting atmospheric properties (temperature and pressure).
  - After landing, each seedwing conducts a surface experiment using pyrotechnic or chemical test which is analyzed using a MEMS sensor for presence of key trace elements.
  - The orbiter or airborne platform emits a signal initiating sequential download of data from each seedwing. A phased array antennae used to locate the source and recover the data.

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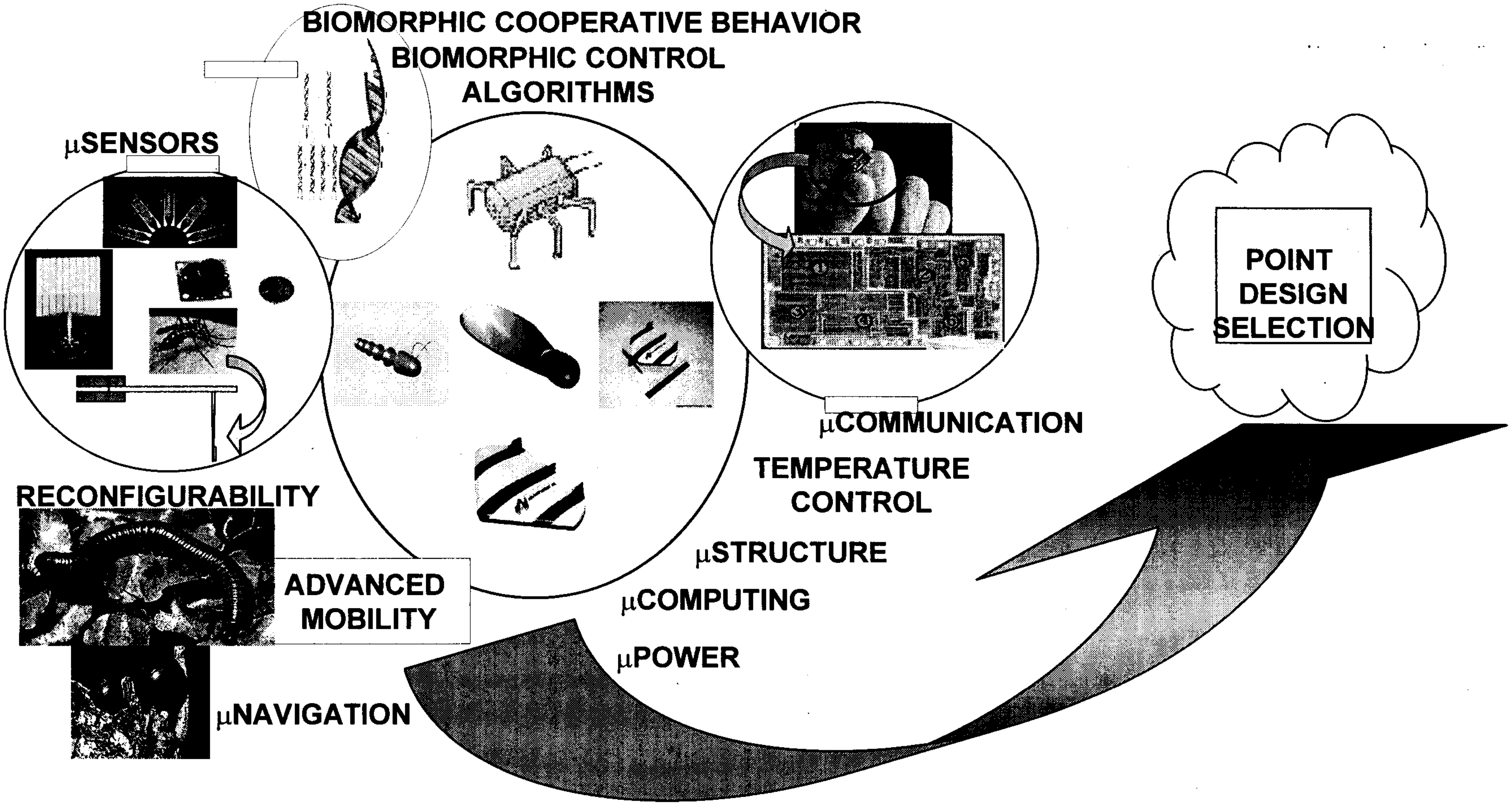
# Biomorphic Explorer: Conceptual Design




***SOME OF THE ISSUES BEING ADDRESSED:***

- ***SYSTEM DESIGN/INTEGRATION***
- ***COMMUNICATION NEEDS***
- ***BIOMECHATRONIC DESIGNS***
- ***CHOICE OF PAYLOAD (SENSORS),***
- ***CONFIGURATION, POWER, SIZE, MASS, SPEED, DEGREES OF FREEDOM***
- ***BIOMORPHIC CONTROLS INNOVATION***
- ***FLEXIBLE, RECONFIGURABLE MOBILE UNITS***

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# COMPARISON OF 1998 BIOMORPHIC SYSTEM DESIGNS

| SYSTEM TYPE | MASS (gram) | VOLUME $cm^3$ | POWER watts | SPEED m/sec | NUMBERS PER MISSION (PAYLOAD ~3 kg) | TERRAIN COVERAGE |
|---|---|---|---|---|---|---|
| BIOMORPHIC FLIGHT SYSTEM | | | | | | |
| GLIDER | 75 | 300 | 3 | 90 | 32 | ALL TYPES ~50Km -100 Km range covered in ~ 10 min |
| SEEDWING FLYER | 60 | 77 | 2.5 | 6 | 25-50 (deployment platform dependent) | ALL TYPES |
| BIOMORPHIC SURFACE/SUBSURFACE SYSTEM | | | | | | |
| WORM ROBOT | 85 | 300 | TBD | 0.003 | 30 | VERY LIMITED* |
| HEXAPOD | 1000-2000 | 750 | 5-10 | 0.1 | 1 | LIMITED ~ 0.06 Km range covered in ~ 10 min |

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* Needs Innovations of biomechatronic design

# COMPARISON OF 1998 BIOMORPHIC SYSTEM DESIGNS

Worm robot is an advanced concept in its infancy that awaits development of an innovative biomechatronic design.

Multipod have been extensively worked on and small quadrupod or hexapod designs using flexible carbon steel legs have been made which can be smaller than the hexapod designed in 1998. Making a hexapod suitable for the rocky mars terrain dictated the design of this science purpose hexapod. Because of its large mass (1-2 Kg), for a biomorphic mission, this design would not be amenable to easy multiplicity.

When considering the specific applications of wide area coverage for site selection via imaging and collecting atmospheric data from multiple points, the glider clearly stands out as the choice because its low mass, high payload fraction and its large range allows terrain coverage of 50-100 Km in just about ten minutes. Additionally the technology to build a small glider can be readily leveraged from the recent developments in micro air vehicles. So, the glider was selected for end to end baseline conceptual design development

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# COMPARISON OF DIFFERENT MARS EXPLORER TYPES

| PLATFORM | IMAGERY,TARGET, AND SITE CHARACTERISTICS |
|---|---|
| GLIDER | • CLOSE TO WALLS IMAGING FOR EXCELLENT SPATIAL RESOLUTION<br>• IN FLIGHT ATMOSPHERIC MEASUREMENTS, MULTIPLE LOCATIONS, SIMULTANEOUSLY<br>• CAN TRAVERSE RUGGED TERRAIN, LARGE RANGE, HIGH COVERAGE DENSITY<br>• EXCELLENT NAVIGATION AND TARGETING CONTROL, PROVIDES SITE DIVERSITY<br>• LOW COST PLATFORM ALLOWS REDUNDANCY, LOW MISSION RISK, HIGH PAYLOAD FRACTION |
| ORBITER | • HIGH SPATIAL RESOLUTION POSSIBLE<br>• COMPOSITION POSSIBLE, BUT AT POOR SPATIAL RESOLUTION<br>• STEEP VERTICAL WALLS ARE POORLY RESOLVED |
| LANDER | • DISTANCE FROM WALLS LEADS TO POOR RESOLUTION<br>• NEAR FIELD OBSTRUCTIONS MAY LIMIT VIEW OF PRIMARY TARGETS<br>• NO TRAVERSE CAPABILITY |
| ROVER | • TRAVERSE LIMITED TO 1 TO 3 km OVER PERIOD OF DAYS<br>• CANNOT ACCESS MULTIPLE SITES<br>• CANNOT ACCESS STEEP AND ROUGH WALL SLOPES |
| BALLOON | • NO ABILITY TO CONTROL TARGET SITES<br>• SENSITIVITY TO LOCAL WINDS, RAPID TEMPERATURE AND PRESSURE FLUCTUATIONS |
| POWERED AIRCRAFT | • LOWER PAYLOAD FRACTION<br>• MORE MASS, MORE POWER, LARGER WINGSPAN, ASSOCIATED ADDITIONAL COSTS<br>• HIGHER COSTS & LARGER SIZE REDUCES MULTIPLICITY |

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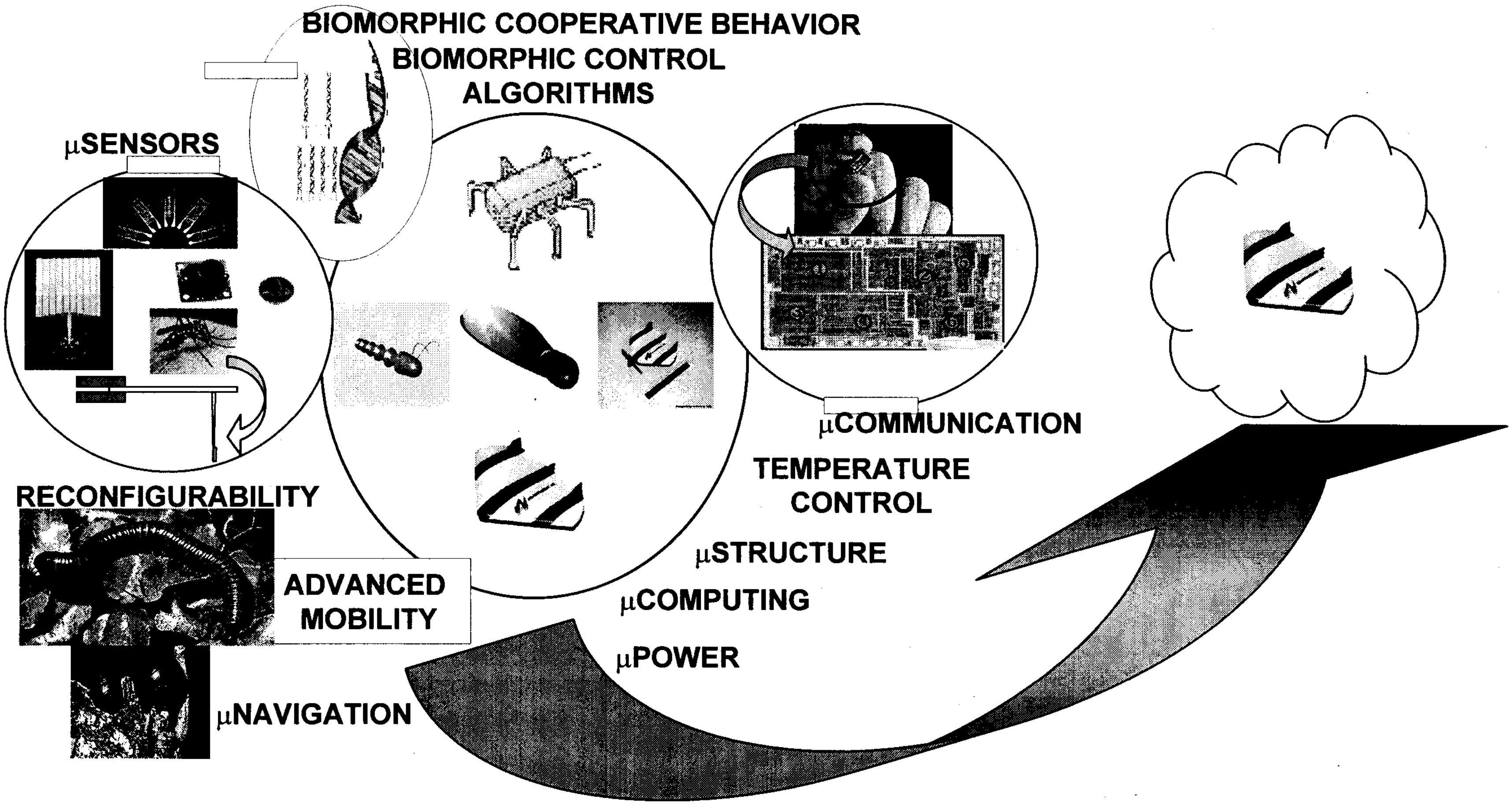
# Biomorphic Explorer: Conceptual Design




***WINNING CONSIDERATIONS:***

- *LOW MASS < 100 g*
- *HIGHER PAYLOAD FRACTION > 50%*
- *LARGE RANGE OF AERIAL MOBILITY ~ 50 Km to 100 Km*
- *ACTIVE CONTROL EXECUTABLE*
- *SOLAR NAVIGATION*
- *SOARING FLIGHT IN RISING CURRENTS*
- *COOPERATIVE MISSION SCENARIO : EASY MULTIPLICITY*

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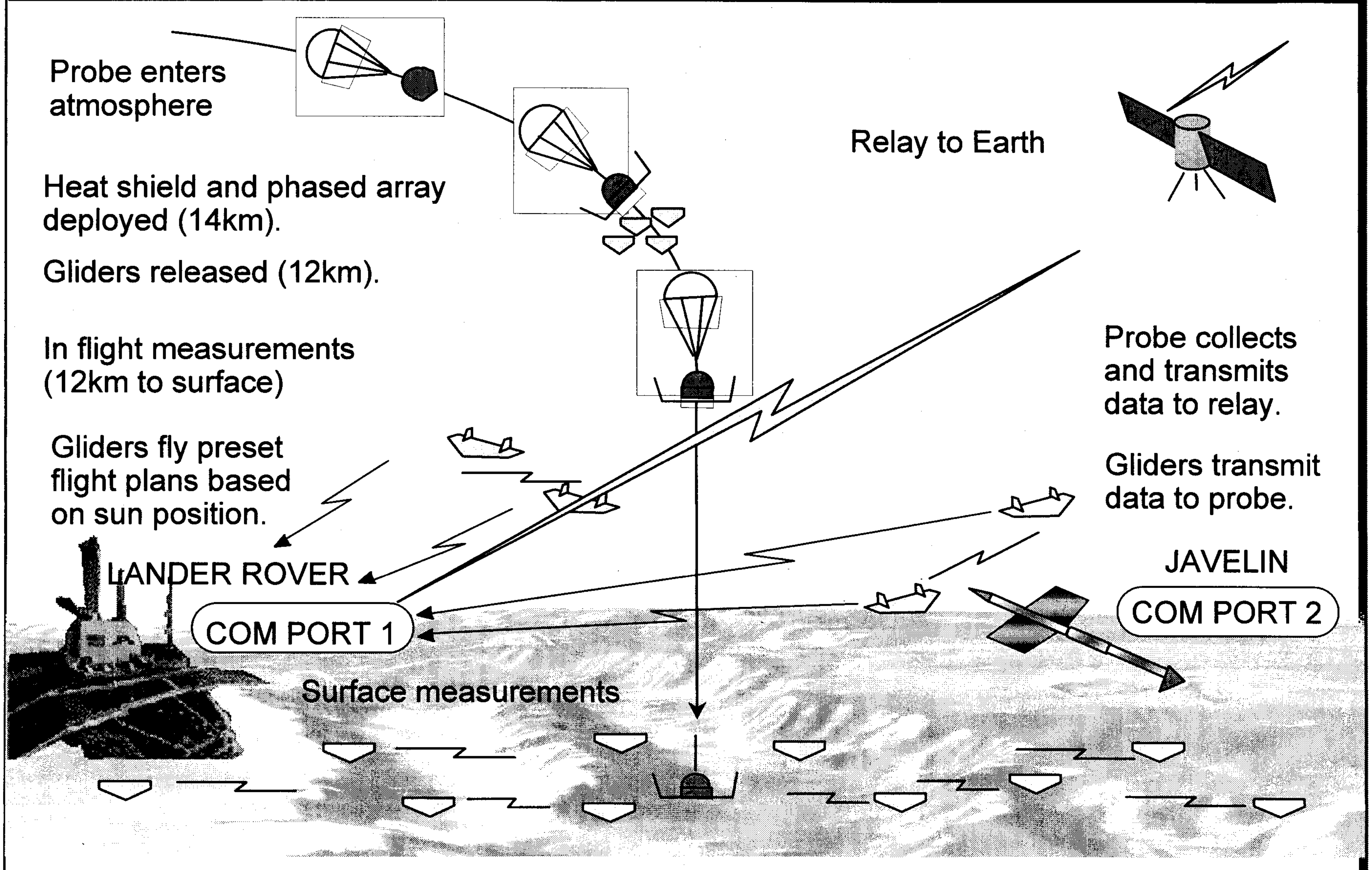
# Biomorphic Glider Deployment Concept (Probe Deploy/Lander Relay)

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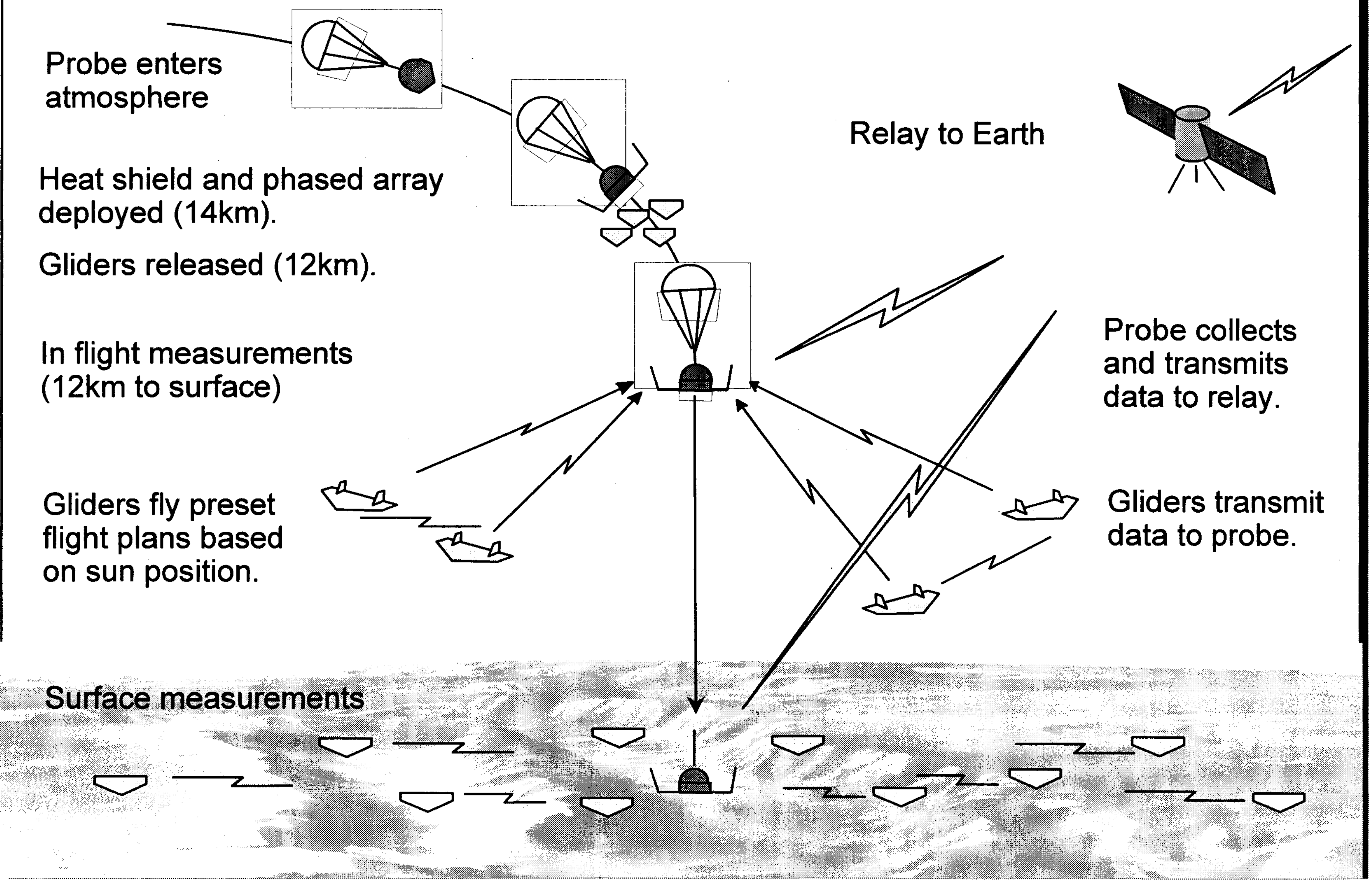
# Biomorphic Glider Deployment Concept: Probe Deploy/Probe Relay

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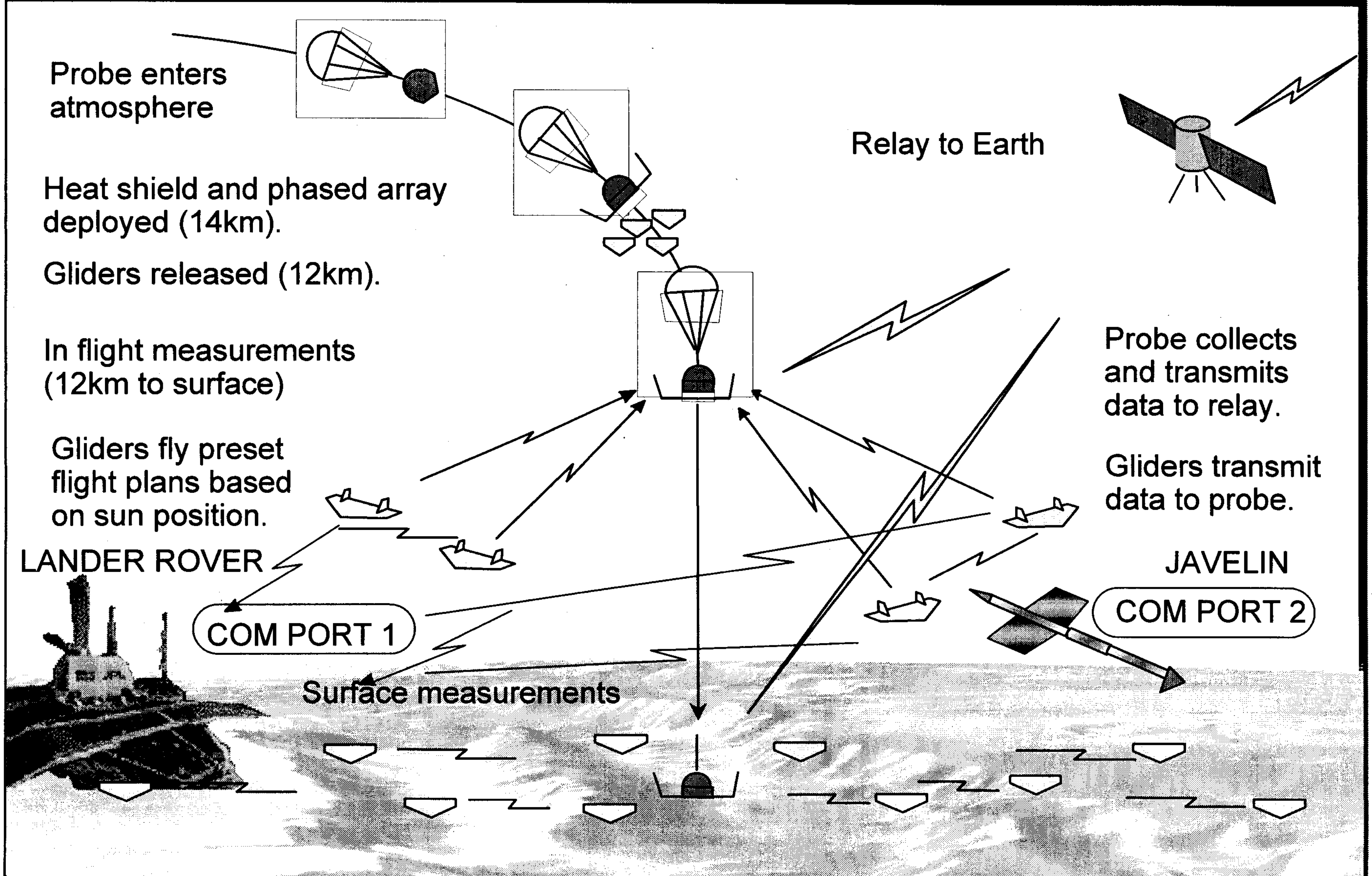
# Biomorphic Glider Deployment Concept: Probe Deploy/ Dual Relay

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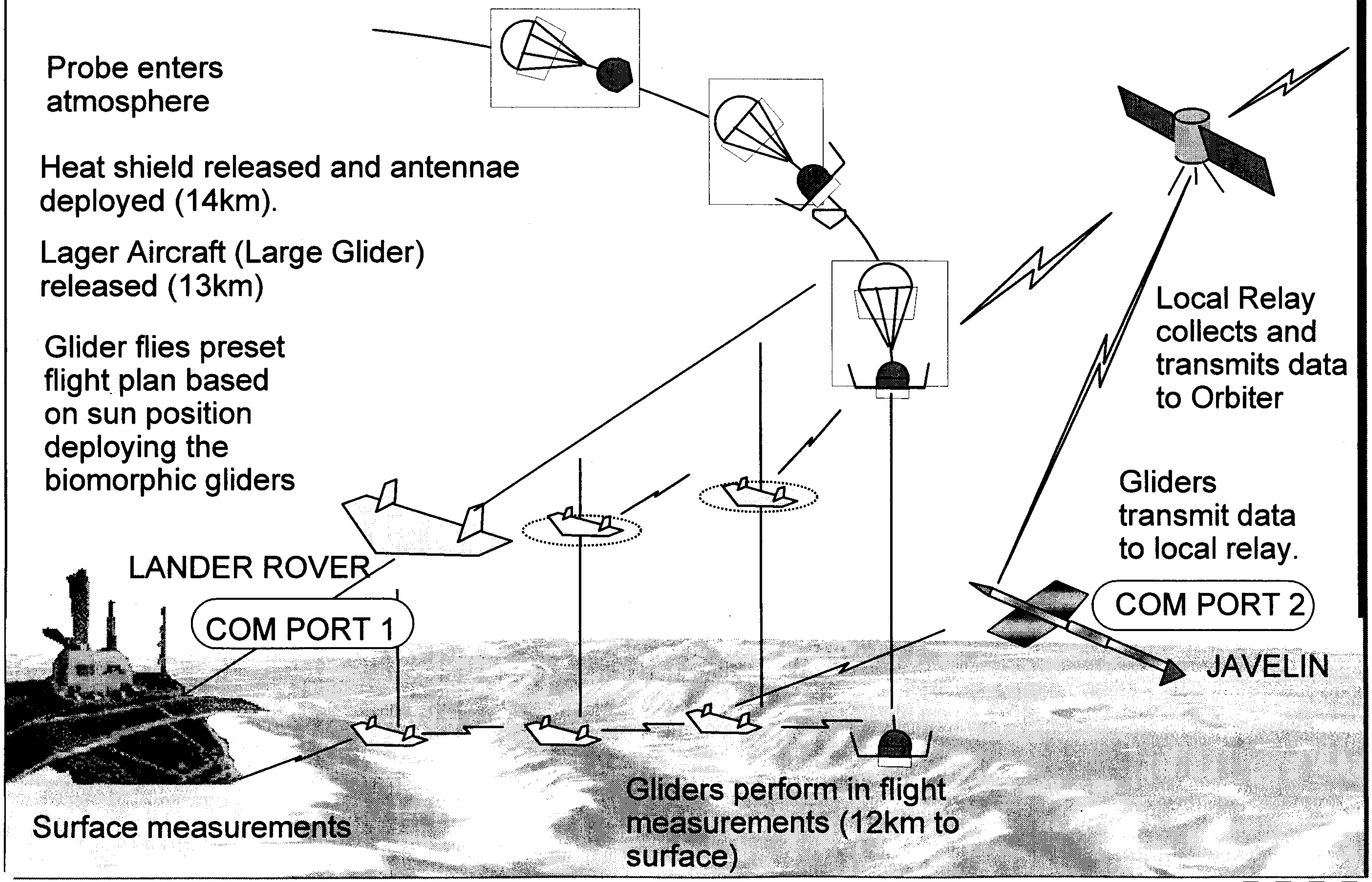
# Biomorphic Glider Deployment Concept (Larger Aircraft/Glider Deploy)

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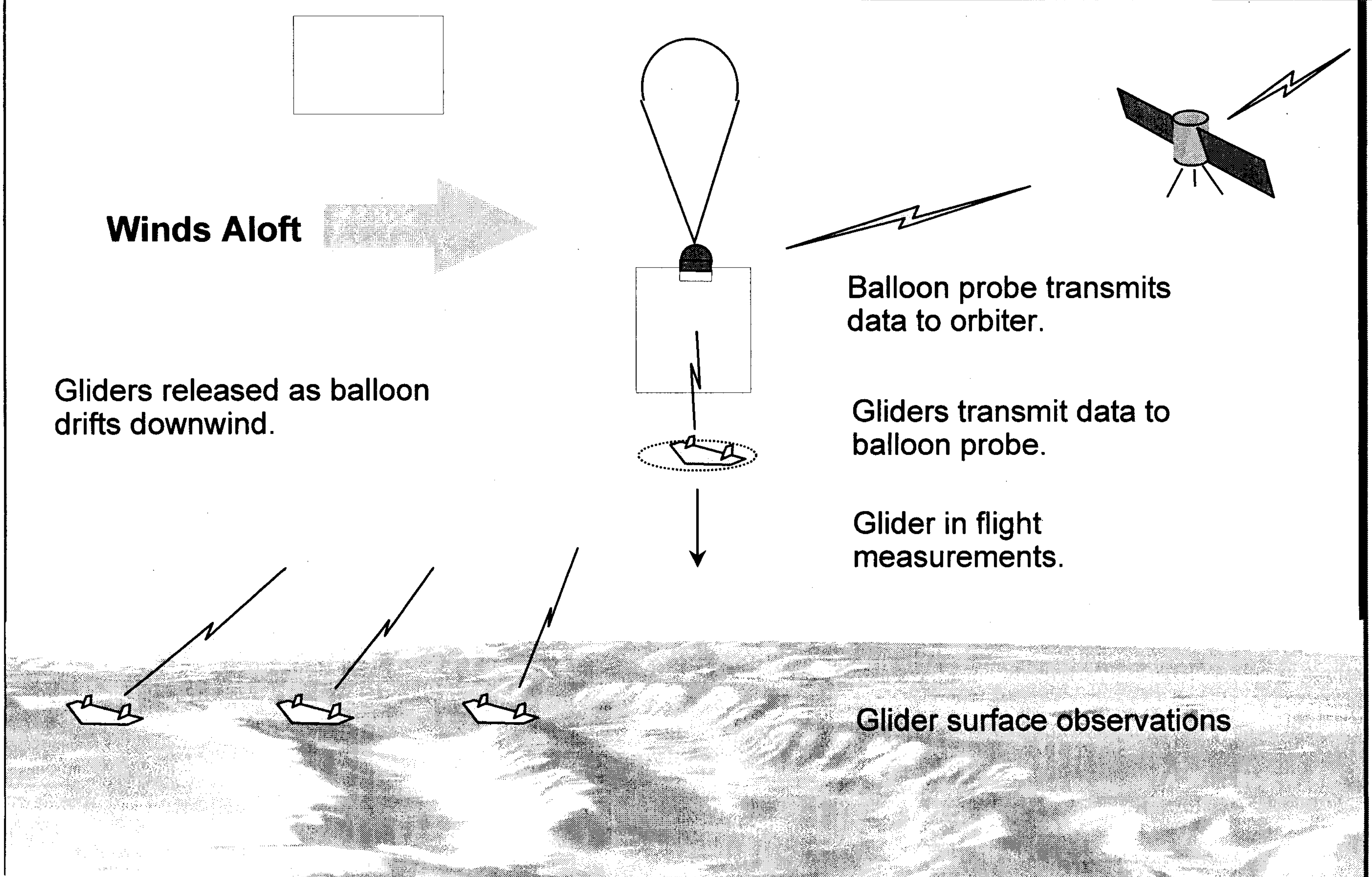
# Biomorphic Glider Deployment Concept (BalloonDeploy/BalloonRelay)

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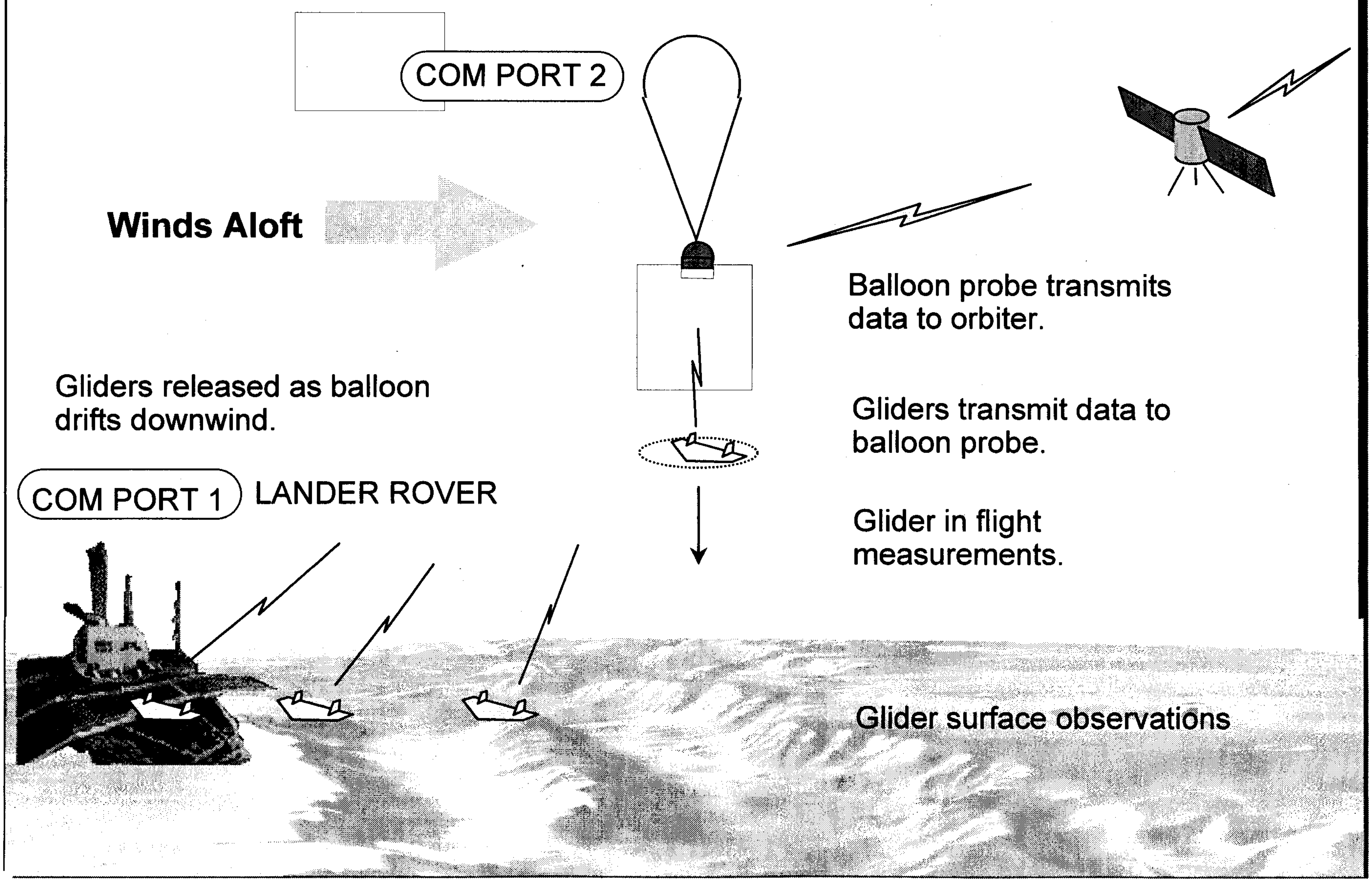
# Biomorphic Glider Deployment Concept (BalloonDeploy/Dual Relay)

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# Biomorphic Gliders

- Small, simple and low cost system ideal for reconnaissance and wide area dispersion of sensors and small experiments.
- Payload mass fraction 50% or higher.


| | | | Baseline | | |
|---|---|---|---|---|---|
| Total Mass | = | 57 | 75 | 250 | 500 gm |
| Payload Mass | = | 32 | 47 | 150 | 300 gm |
| Wing Span | = | 0.19 | 0.25 | 0.50 | 0.76 m |
| Wing Area | = | 0.014 | 0.021 | 0.071 | 0.143 m^2 |
| Volume | = | 168 | 300 | 1700 | 5200 cm^3 |
| Flight Speed | = | 90 | 90 | 90 | 90 m/s |
| Range | = | 50 | 55 | 72 | 83 km |
| Duration | = | 590 | 650 | 800 | 1300 sec |
| Glide Ratio | = | 5.3 | 5.8 | 7.5 | 8.6 |
| Starting Alt. | = | 10 | 10 | 10 | 10 km |

- Performance calculations based on conditions at 5km altitude.
- Volume based on projected area x mean thickness x 1.2

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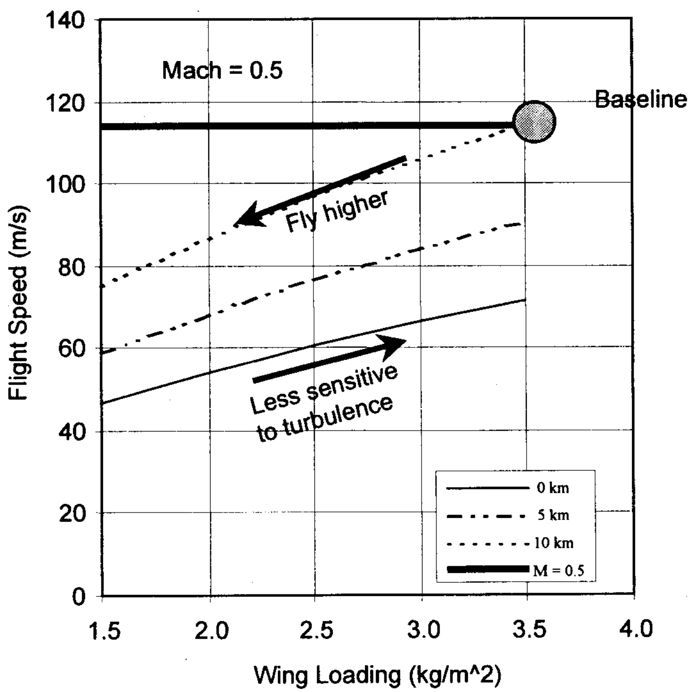
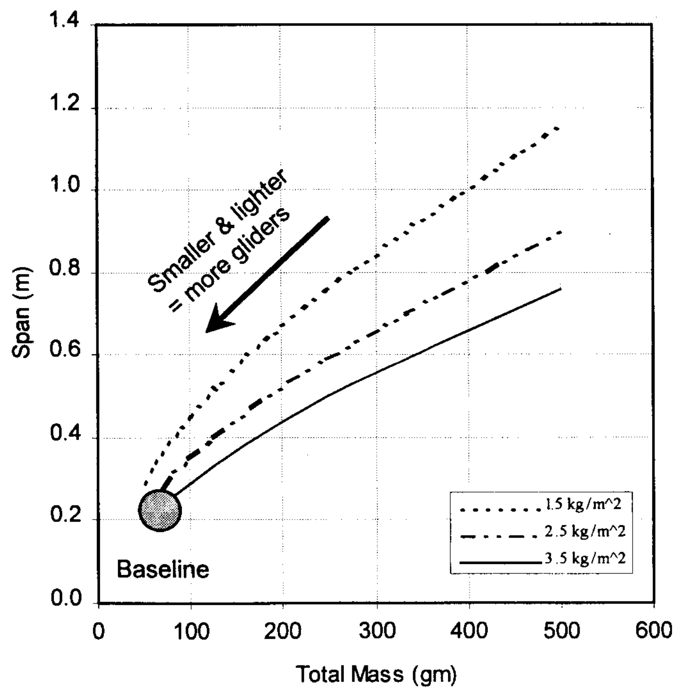
# Biomorphic Glider Design Parameters

- High wing loading reduces sensitivity to atmos. turbulence.
- Low wing loading permits higher deployment altitude.
- Max. wing loading constrained by Mach = 0.5 at 10km altitude.




- High wing loading reduces wing span (packing volume).
- The maximum number of μgliders is achieved with minimum mass and maximum wing loading.

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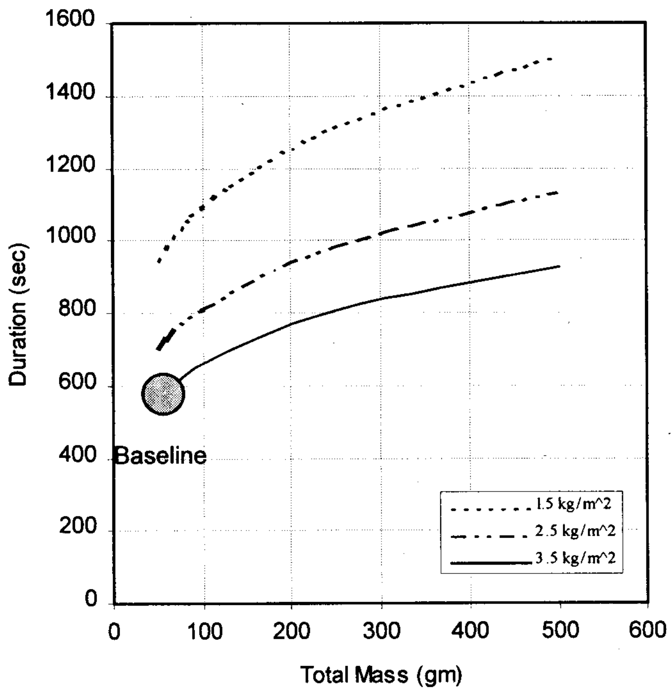
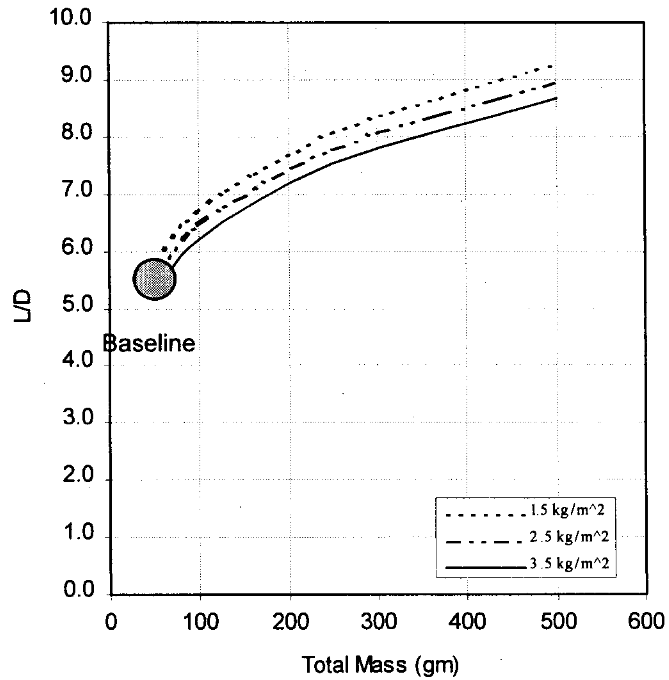
# Biomorphic Glider Performance

- Long duration achieved with low wing loading or larger scale.

- Range (L/D) is not very sensitive to wing loading.
- Range increases with scale due to Reynold's Number effect.




Wing Cl =0.3

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# Biomorphic Glider Optimization

- **Payload mass determines glider mass**
  - Deterministic design process
  - Payload mass fraction ~50%
  - Goal is always to minimize payload mass and power requirement
- **When mission objective is to widely disperse scientific payloads and maximize number of in situ measurements**
  - Maximize number measurements (i.e. number of gliders) = high wing loading, small size
  - Maximize dispersal = long range (L/D), (duration unimportant)
- **When mission objective is to maximize time aloft for atmospheric sampling**
  - Trade-off for maximum total time aloft for swarm (few larger gliders with low decent rate and higher starting altitude, or many smaller gliders with lower performance)

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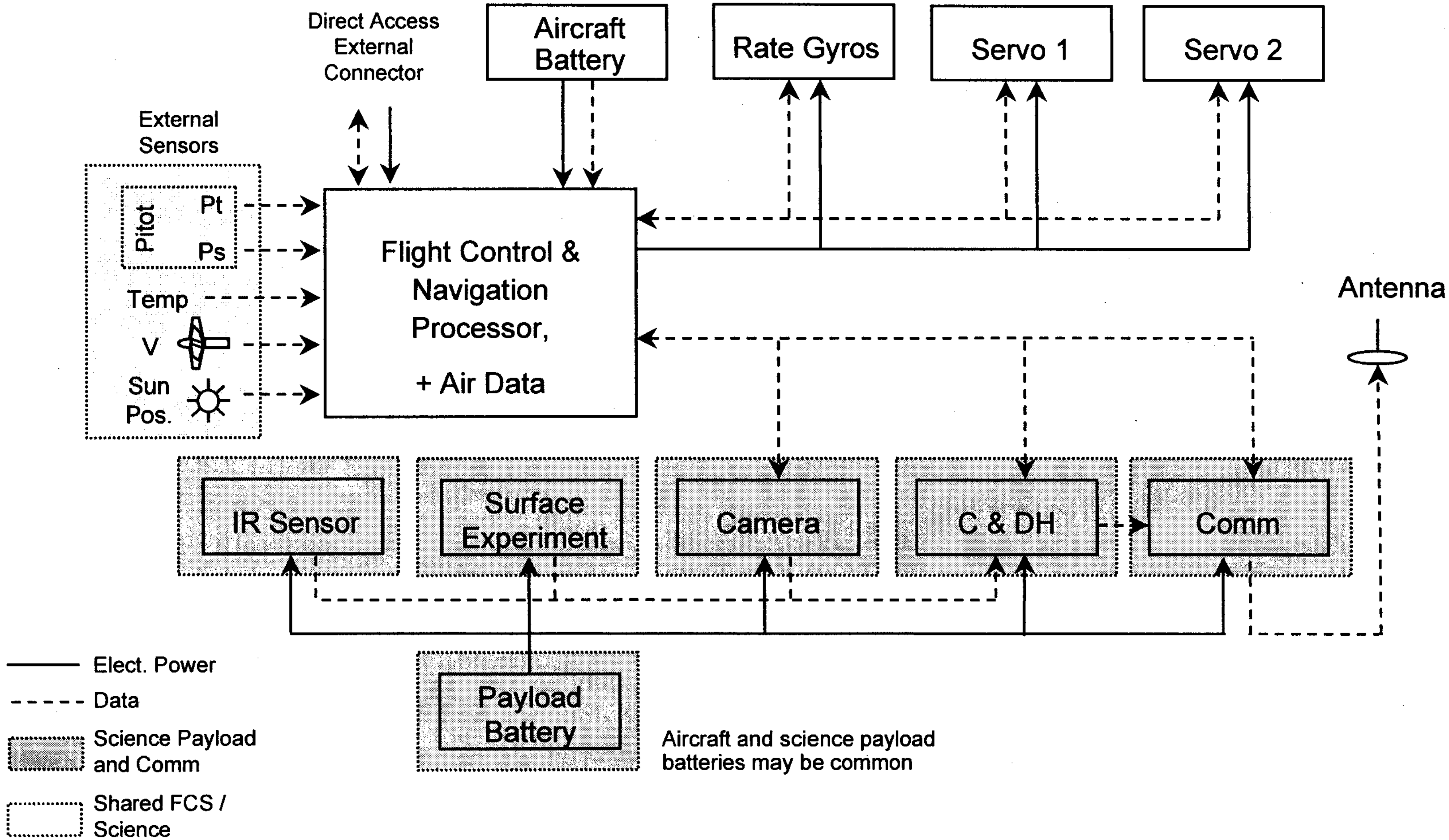
# Biomorphic Glider System Diagram




Aircraft and science payload batteries may be common

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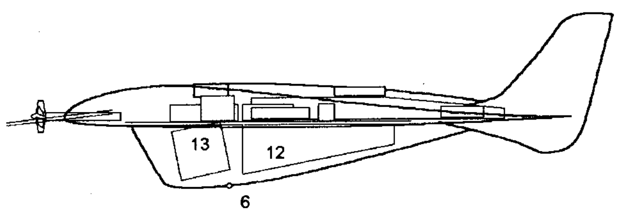
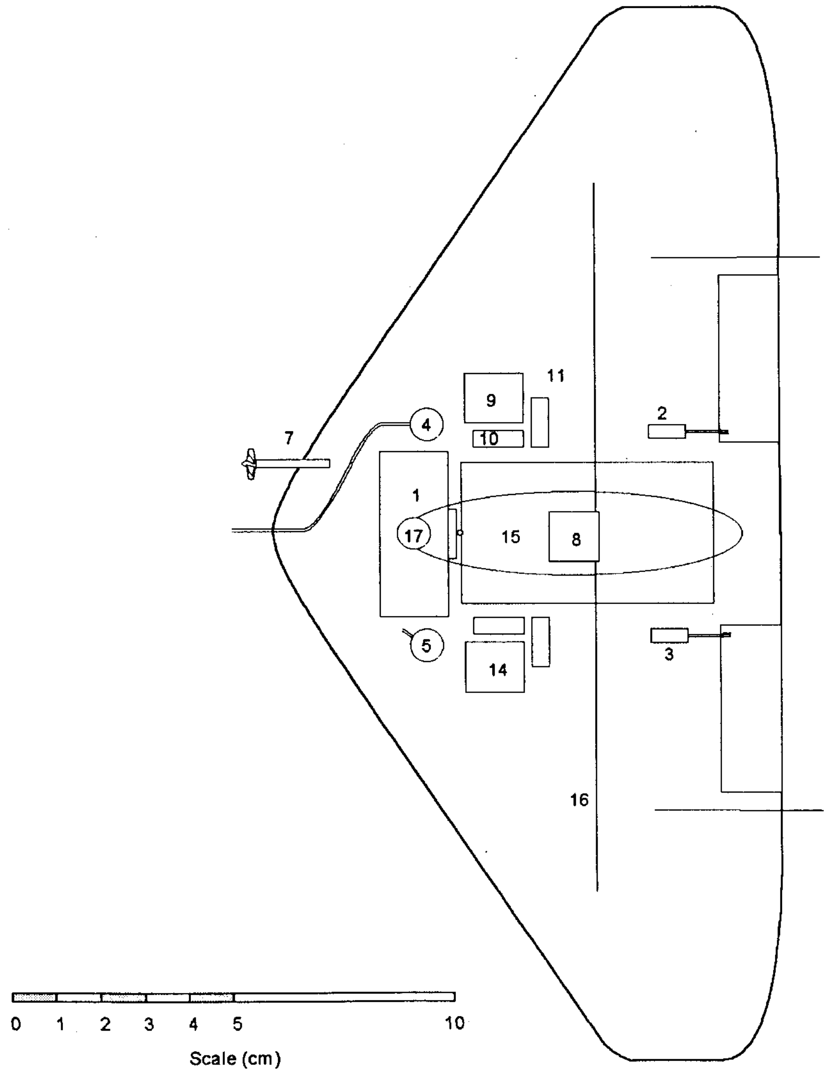
# 75gm Biomorphic Glider Internal Arrangement

- **System Components**
  1. Battery, Li 400mAh**
  2. Right elevon servo
  3. Left elevon servo
  4. Total pressure sensor
  5. Static pressure sensor**
  6. Temperature sensor**
  7. Airspeed sensor**
  8. Sun position sensor**
  9. Flight controls computer
  10. Pitch rate sensor (2)
  11. Roll rate sensor (2)
  12. Surface experiment*
  13. Camera*
  14. C & DH*
  15. Communications*
  16. Antennae*
  17. IR sensor*

* Payload elements
** Shared payload /aircraft

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# 75gm Biomorphic Glider Mass / Power Budgets

| *Item* | *Mass (g)* *Glider* | *Payload* | *Peak Power (W)* | *Average* Power (W)* | *Description* |
|---|---|---|---|---|---|
| 1 Battery | 7.0 | 7.0 | - | - | Li 400mAh, LTC-311 |
| 2 Right elevon servo | 0.5 | | 0.200 | 0.200 | AV experience, micro geared servos |
| 3 Left elevon servo | 0.5 | | 0.200 | 0.200 | |
| 4 Total pressure sensor | 0.2 | | 0.010 | 0.010 | IMMI IMP 2000 |
| 5 Static pressure sensor | 0.2 | | 0.010 | 0.010 | IMMI IMP 2000 |
| 6 Temperature sensor | | 0.2 | 0.025 | 0.025 | Si or Platinum chip** [Iksan,Jumo] |
| 7 Airspeed sensor | 1.5 | | 0.005 | 0.005 | Servo motor / anemometer |
| 8 Sun position sensor | 1.0 | | 0.005 | 0.005 | Four element photocell |
| 9 Flight controls computer | 1.0 | | 0.050 | 0.050 | AV experience, incl. some A-D conv. |
| 10 Pitch rate sensor (2) | 2.0 | | 0.120 | 0.120 | AV experience, Murata piezioceramic |
| 11 Roll rate sensor (2) | 2.0 | | 0.120 | 0.120 | |
| 12 Surface experiment | | 12.0 | 10.000 | 0.050 | Payload Reserve*** |
| 13 Camera | | 20.0 | 0.250 | 0.050 | JPL Miniature Camera Design |
| 14 C & DH | | 2.0 | 0.050 | 0.050 | Incl. some A-D conv. for science instr. |
| 15 Communications | | 5.0 | 10.000 | 2.000 | JPL / CALTECH Design |
| 16 Antennae | | 0.3 | - | - | JPL/CALTECH Design |
| 17 IR sensor | | 0.3 | 0.200 | 0.200 | *** |
| 18 Airframe / IC / Misc. | 12.0 | | - | - | Composite / ribbon / misc. |
| Subtotal | 27.9 | 46.8 | | | |
| **Total** | **75** | | **21.245** | **3.095** | |

* *Average power consumed with duty cycle over 600sec flight.*
** *Data reflects device noted or next generation of device.*
*** *TBD*
*Note: Battery mass shared between payload and glider systems.*

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# System Component Descriptions

## 1. Battey

Eagle Picher LTC-311 (13gm, 350mAh) or two LTC-314 (7gm, 150mAh ea). These have been discharge tested at varous rates for the MAV project, values are apropriate for 3W discharge rate.

Power conversion is ideally not needed. Two LTC-314 cells provide a working voltage of about 6V which can be used for most subsystems. Any components requiring a different voltage can be handled using a small linear voltage regulator or PWM converter at a cost of 1 to 2gm. (Mfg. include Telcom or Nat. SemiConductor).

## 2 & 3. Servos

The servos are being developed for the MAV SBIR program.

| | |
|---|---|
| Current working units: | 0.46 grams |
| | 2 mW power consumption |
| | 6 grams max. linear force |
| | 4 mm travel |

Better devices will be available in a few months, based on 0.3 gm RMB micro brushless DC motor.

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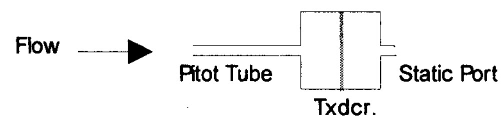
# System Component Descriptions

## 4 & 5. Pressure altitude measurement

Atmospheric pressure is normally used to schedule control system gains. However, it is difficult to measure on Mars due to the low pressures (3mb - 7mb). There are two solutions to this problem.

A. True airspeed (anemometer) and dynamic pressure (pitot tube) are measured and used to compute atmospheric density. These parameters are sufficient for control gain schedules. The dynamic pressure will be about 0.6mbar and the Velocity about 100m/s.

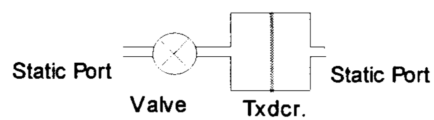
Pressure sensor: MEMS Thin film technology, IMP 2000-005, 0.5inH2O (1mbar) full scale, ~1% accuracy, thermal compensated, linear output with built in ASIC amplifier. ~1 gram, ~1 cm^3.




dP = Dynamic Pressure

B. Direct pressure measurement using absolute pressure sensor. Current sensors with range to handle Earth's pressure do not have the sensitivity for the Mars atmosphere. In this approach, use an appropriately scaled differential sensor for Mars and a valve. The valve is left open until cruise to avoid loading the sensor, then closed to capture the reference vacume.

Sensor: MEMS Thin film technology, IMP 2000-04, 4.0inH2O (10mbar) full scale, ~1% accuracy, thermal compensated, linear output with built in ASIC amplifier. ~1 gram, ~1 cm^3.



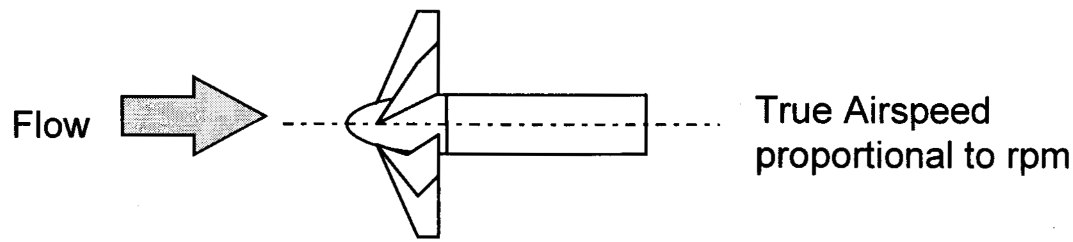
# System Component Descriptions

## 6. Temperature

Standard thermistors, Si or Platinum chip from Iksan or Jumo.

## 7. Airspeed sensor

Based on the 0.3 gm RMB micro brushless DC motor fitted with propeller. Drive windings used as sense windings which give a sinusoidal signal proportional to shaft rotation. Total mass with mount and wires ~1gm. Initial prototype units developed as part of MAV projects.

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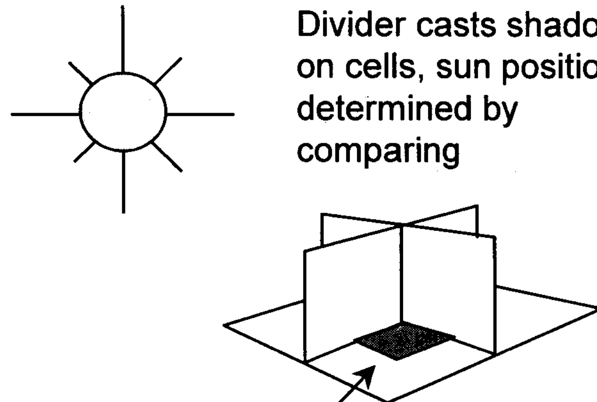
# Glider Navigation Strategy

## • Solar Navigation

- Simplest instrument and control strategy that would insure random dispersion of gliders (similar to old heat seeking missile guidance)
- Not suitable for night time or near solar noon
- Flight plans unique for each glider and include:
  - maintain constant heading based on sun position for maximum range
  - heading varies with time to limit range




## • Options

- Increased accuracy of solar navigation using photocell array and optics
- Incorporate RF directional capability to glider and steer by ground or orbital beacon

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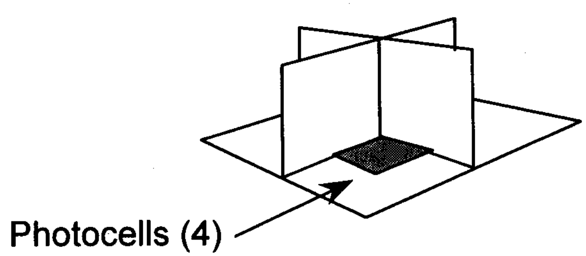
# System Component Descriptions

## 8. Sun position sensor

Hamamatsu or Honeywell quadrature sensor similar to those used to focus lasers in DC players or custom Si photodiode.

Dale Reed (NASA DFRC) developed an approach using a simple quadrature sensor for unmanned aircraft navigation and reference measurement.

Can custom make a sensor using photocells.

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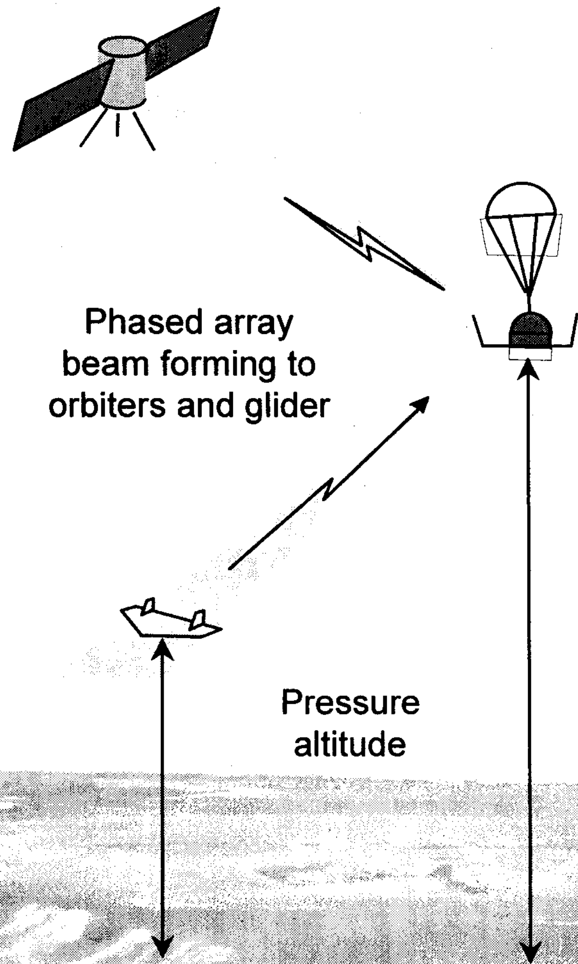
# Glider Locating Strategy

- **Position Inferred from Data**
  - Entry point + flight plan + glider performance + pressure altitude + images => approximate position
- **Probe Relay Phased Array**
  - Glider position relative to probe determined by beam direction and glider pressure altitude
  - Probe approximate position tracked by orbiters or using same phased array and orbiters
- **Options**
  - Lander equipped with phased array

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# System Component Descriptions

## 9. Flight Control Computer

MAV prototypes use a PIC chip with A-D capability, (pulled silicon chip out of ceramic housing to reduce mass). Use 3 digital outputs as square-wave power to drive the 3 phases of each servo motor. Mass of 1 gram and 0.05W power is based on MAV systems plus margin.

Current implementation is "pilot-in-the-loop". There is no navigation or auto-stabilization system required (although we have used piezoceramic rate gyros for stability augmentation).

## 10 & 11. Rate Gyros

Based on the Murata ENC-05 piezo-ceramic vibratory gyros used in virtual reality systems. Normally weighs few grams, but removing packaging reduces weight to 0.9 gm. Power consumption = 0.02 W. Sensors have large drift due to temperature variations. Use two rate gyros, one reversed in direction, sum signals, add minor hardware to solve drift problem.

# System Component Descriptions

## 13. Cameras typically used on Micro Air Vehicles (MAV's) to date

MAV prototypes currently use Welch Allen series of lightweight CMOS imagers. These are PCB level cameras without lens housings. Input is 250mW, output is NTSC analog video.

- Low Res B&W, 320 x 240 pixels, 1.3 grams
- High Res B&W, 510 x 488 pixels, 1.9 grams
- High Res Color, 510 x 488 pixels, 2.1 grams

MIT-Lincoln Labs is currently working on a 1000 x 1000 pixel camera for the DARPA MAV program with a total mass of 2 gm (including lense), 1 cubic centimeter.
This baseline design provides mass margin for inclusion of a science stereo camera detailed further in the measurement strategies section.

## 14. C & DH

TBD. Dependent on instruments, data requirements and transmitter.

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# Glider Comm Strategy

- **Entry Probe as Comm Relay**
  - Vantage point above gliders with lower rate of descent insuring good comm link even with gliders on surface
  - Gliders can transmit using optimal self-organized, self-routing network
  - Can tailor comm design to mission
  - Entry probe becomes lander and maintains comm link to glider network for long term surface measurements
- **Options**
  - Use existing lander as comm relay
    - low cost
    - limits site selection
    - risk that entry error puts some gliders out of range
  - Deploy separate lander
    - permits site flexibility
    - added cost

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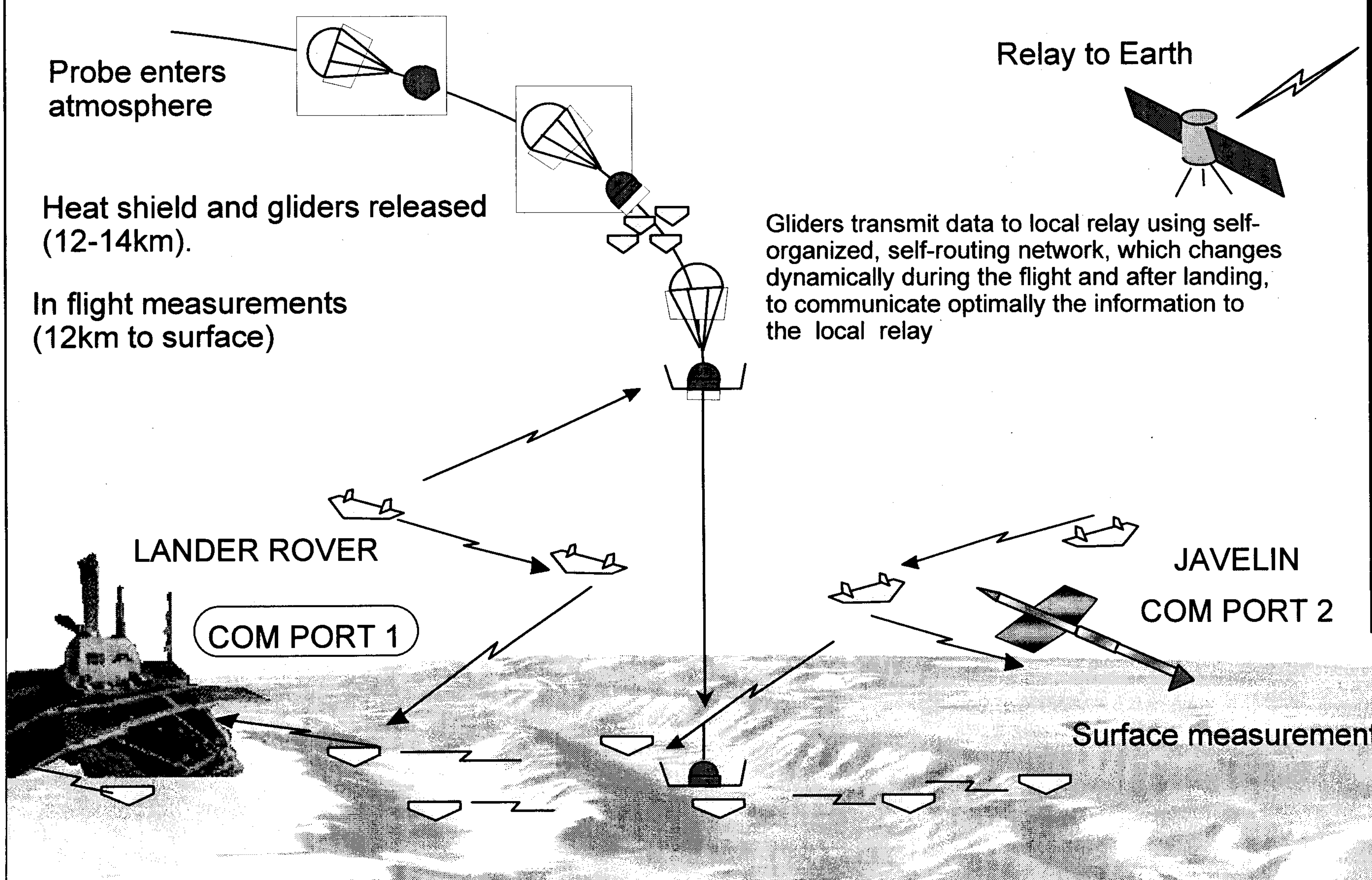
# Biomorphic Glider Deployment/Telecommunication Concept

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# System Component Descriptions

## 15. Telecommunications

The proposed communication plan for the gliders and the lander/relay is based on a self-organized, self-routing network, which changes dynamically during the flight and after landing. The network is based on short range communication between the glider to route the information to the lander /relay by forming a self configured, amorphous network of multiple hubs (gliders). The glider transciever will be implemented using monolithic integrated circuit technology to minimize the number of discrete components and hence lower the cost, failure susceptibility and weight of the glider units allowing them to carry payload and achieve longer data collection lifetime. The possibility of direct communication between the gliders and the orbiter (at a much lower rate) also makes the system more tolerant to possible failures in the relay unit. A glider transciever weighing ~ 5 g, consuming less than 2W total average power in a package of < 3cm x 6cm x 1cm, heat sink included can be designed and developed.

# System Component Descriptions

## 16. IR sensor

TBD. 200nm to 1200nm wavelength available off the shelf from Hamamatsu or Honeywell .

## 17. Airframe / Misc.

MAV sturdy airframes typically weight about 5 grams for a total system weight of 55 grams. Construction is typically using carbon fiber, fiberglass, hardwood, balsa wood, and plastic foams.

12 grams is assumed for the structural weight of the 75 gram Biomorphic Glider which should be sufficient for the airframe and other misc. components including materials substitution for space application.

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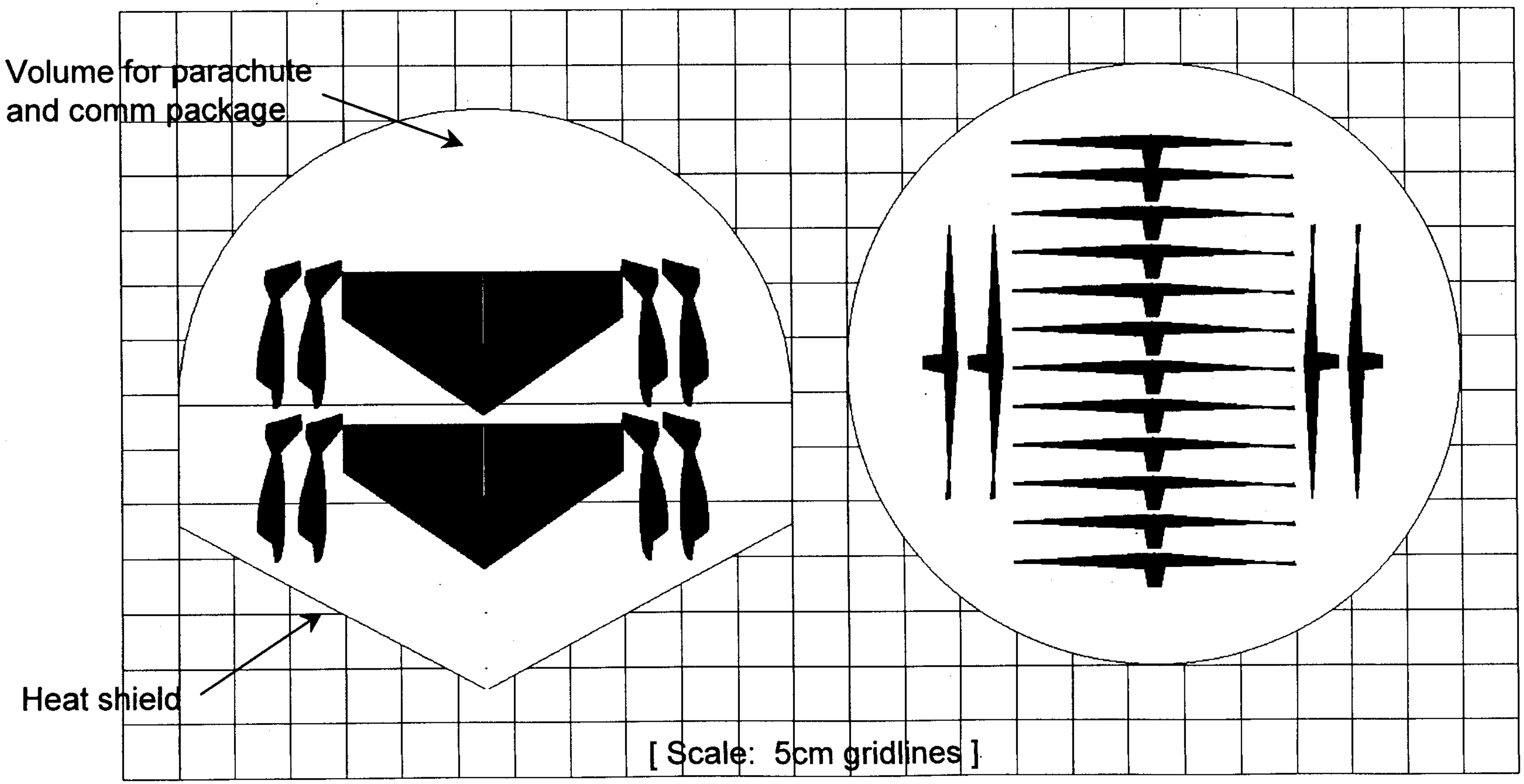
# 75gm Biomorphic Glider / Probe Integration

- 32 gliders packaged into ASAP compatible self righting probe.

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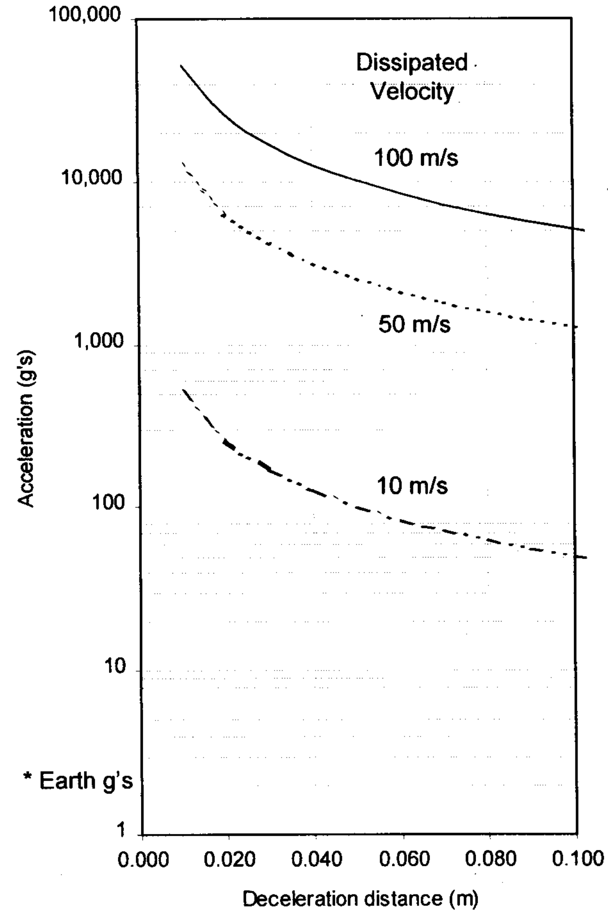
# Biomorphic Glider Landing Survivability

- **Initial Conditions**
  - 72m/s horizontal flight speed at 0km
  - 13m/s descent rate at 0km
- **General Considerations**
  - Impact trajectory is at an angle to flat surface. Some gliders may have a direct impact on a rock and not survive,... but there are many gliders.
  - Electronics and sensors are all very low mass integrated or discrete surface mounted devices designed for several 1000's of g's - need roughly 2cm to dissipate half the flight speed
  - Battery has highest mass. Can be mounted with crush zone and wire leads for power to the PCBA so that it can break free and not loose electrical connection.
  - Surface experiment most vulnerable, MEMS technology most likely to survive hard landings.
  - Airframe and flight systems expendable

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# *SCIENCE APPLICATIONS*

....WHICH WOULD BE ENABLED/ENHANCED BY SUCH EXPLORERS.....

- VALLES MARINERIS EXPLORATION
  - ONE SINGLE SITE RICH IN GEOLOGIC UNITS
  - STUDY STRATIGRAPHIC COLUMN TOP TO BOTTOM ALONG THE CANYON WALL
  - OPTIMUM SCIENCE SAMPLE SITE

  ....imager, temperature sensor, pressure sensor, sniffer. e-nose, individual gases, elements etc

- SCOUTING FOR CONDITIONS COMPATIBLE WITH LIFE TO LEAD US TO THE SPOTS THAT MAY HOLD SAMPLES OF EXTINCT/EXTANT LIFE
  - WIDE AREA SEARCH WITH INEXPENSIVE EXPLORERS EXECUTING DEDICATED SENSING FUNCTIONS

  ....Individual gases, sniffer: e-nose, chemical reactions, pyrotechnic test, elements, specific amino acids, signatures of prebiotic chemistry etc

- GEOLOGICAL DATA GATHERING:
  - DISTRIBUTED TEMPERATURE SENSING
  - SEISMIC ACTIVITY MONITORING
  - VOLCANIC SITE

  ....Multitude of explorers working in a cascade or daisy chain fashion co-operatively to fulfill task

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# Objective - Atmospheric Science

•VALIDATION AND PREDICTION OF GLOBAL CIRCULATION MODELS BASED ON THE NEAR SURFACE ENVIRONMENTAL DATA AND BOUNDARY LAYER DATA

•ADDRESS MESOSCALE METEREOLOGY (T, P, Wind, Opacity). TARGET GLIDER CLUSTER TO AN AREA (~ 100 sq. Km) THAT IS DIVERSE

•SPECIFIC TARGET SITES:
- •mouth of a canyon
- •edge of a polar cap
- •outflow channels

•TIME THE RELEASE OF BIOMORPHIC GLIDERS TO OBTAIN THE MEASUREMENT OF EPHEMERAL PHENOMENA SUCH AS DUST STORMS

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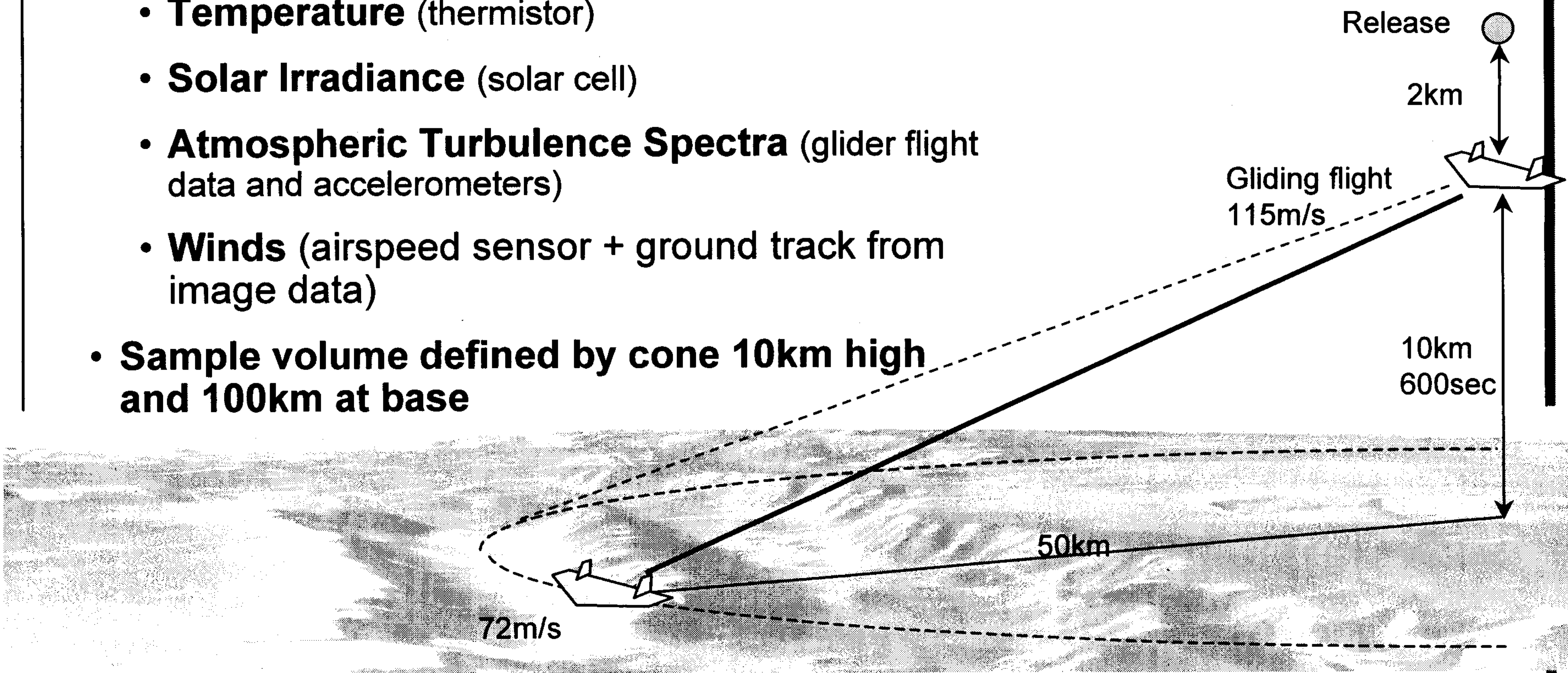
# Biomorphic Glider In-Flight Measurements

- **Meteorology**
  - **Multiple gliders permits analysis of temporal and spatial variations in measurement**
    - **Atmospheric Pressure** (transducer)
    - **Temperature** (thermistor)
    - **Solar Irradiance** (solar cell)
    - **Atmospheric Turbulence Spectra** (glider flight data and accelerometers)
    - **Winds** (airspeed sensor + ground track from image data)
  - **Sample volume defined by cone 10km high and 100km at base**

Total number of measurements =
# Gliders
X # measurements / sec
X flight time

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# WHY ATMOSPHERIC SCIENCE USING GLIDERS

The lower atmosphere is difficult to measure from orbit; infrared remote sensing techniques typically cannot separate the atmospheric contribution from that of the surface in the lowest scale height. Yet the boundary layer, where the surface interaction takes place, is of great importance, being the location of energy transfer in the form of friction, radiation, and conduction.

Direct instrumentation of the lower atmosphere is difficult; usually towers and balloons are employed for this purpose on Earth. The former are massive and the latter temporary. Where horizontal change occurs in the surface, such as in canyons, a network of balloons would be required to observe the range of phenomena. Such topographic regions are important because the winds arising there may help in the origination of dust storms. Dust storms of Martian intensity are unique, and their formation is one of the main problems of planetary atmosphere dynamics.

Glider networks, although temporary, provide a way to sample both laterally and vertically within a short time period, from a single originating point. The spatial scale of coverage, as wide as 100 km, is adequate to span large Martian canyon boundaries. The sampling rate can be high enough to resolve the relevant small scale phenomena within the lowest 10 km. Gliders can be directed to cover particular directions, unlike balloons.

An additional benefit of gliders is the ability to image during descent, providing proof of glide path, determination of wind (together with airspeed), and geologic context at a large range of spatial resolutions.

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# Objective - Imaging & Surface Science

•Detailed Close-Up Imaging and Mapping of the Terrain to enable site selection of potential exobiological sample areas

• Imaging of Valles Marineris
  •one single site rich in geologic units
  •study stratigraphic column top to bottom along the canyon wall
  •optimum science sample site

•Deployment of Surface Science Payloads on potentially interesting but hard to access locations

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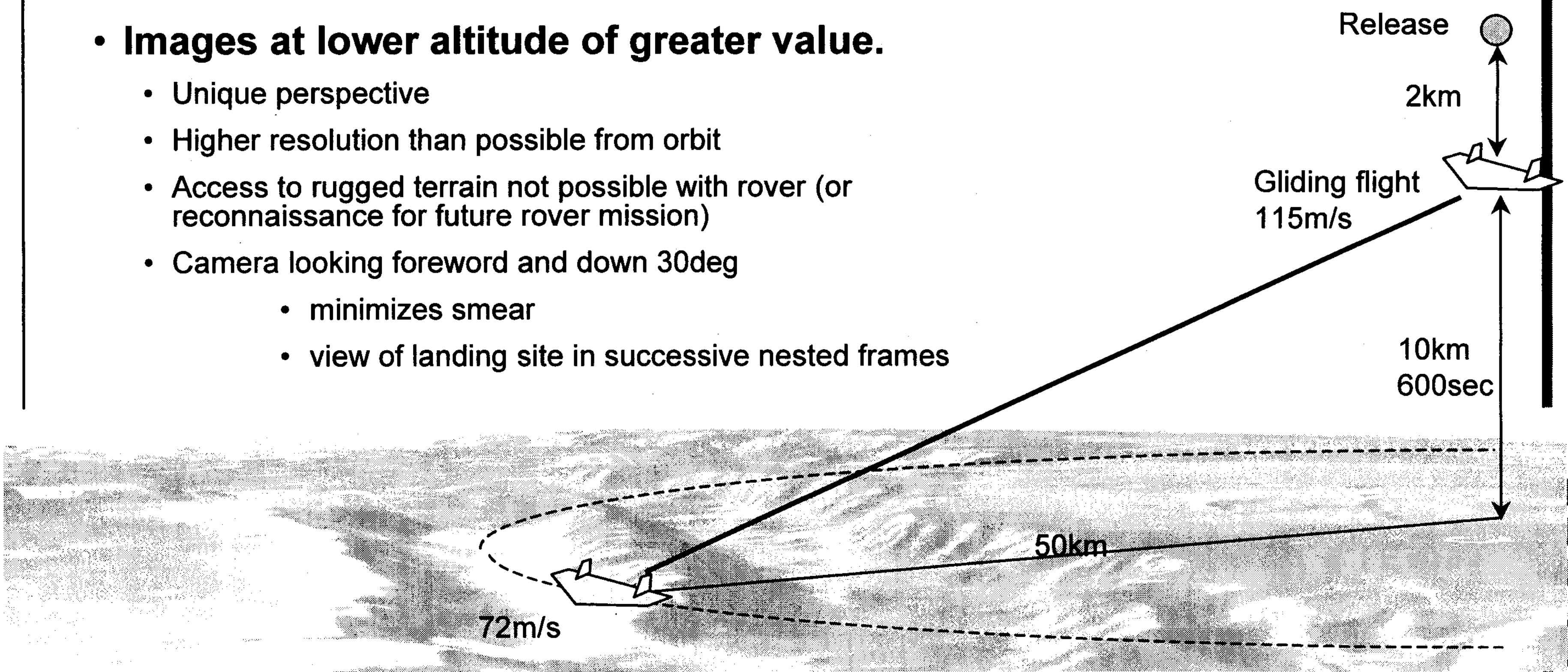
# Biomorphic Glider In-Flight Measurements

- **Imaging**
  - **Images at high altitude of limited science value compared to orbiter (resolution, FOV).**
    - Provides context for low altitude images
  - **Images at lower altitude of greater value.**
    - Unique perspective
    - Higher resolution than possible from orbit
    - Access to rugged terrain not possible with rover (or reconnaissance for future rover mission)
    - Camera looking foreword and down 30deg
      - minimizes smear
      - view of landing site in successive nested frames

Total number of measurements =
# Gliders
X # images

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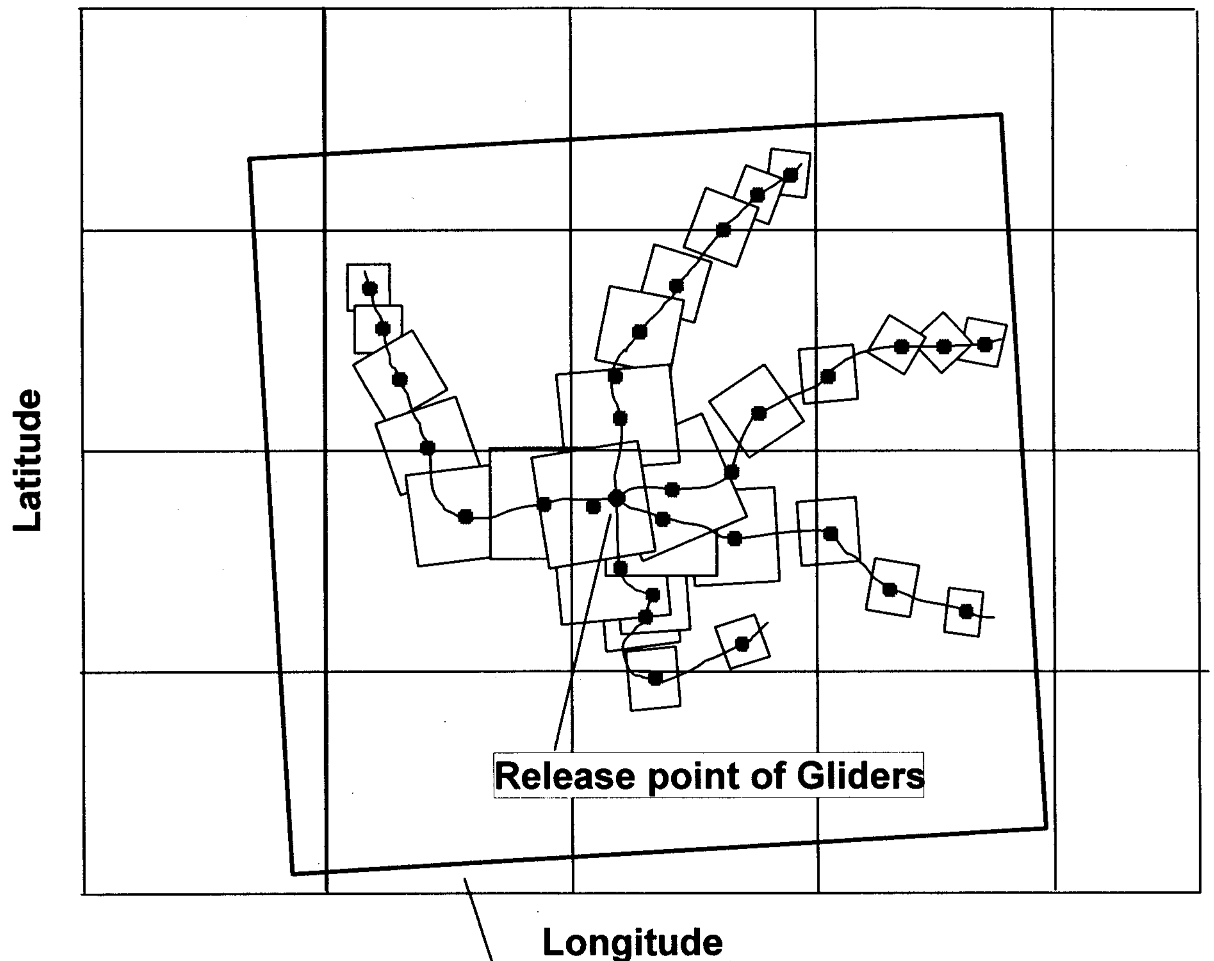
# Footprints of Descent Images




Context frame acquired by carrier vehicle, 100 Km x 100 Km area

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# Miniature Digital Camera Assembly

- Key Elements
  - Active pixel Sensor (APS) Imaging Chip
    - 2-D imaging array using CMOS technology
    - On-chip digital circuitry gives full programmable control to enable digital camera-on-a-chip operation.
    - On-chip camera control functions include: frame rate, exposure parameter, electronic shuttering, analog-to-digital readout.
    - Mass: 5 gm
    - Grayscale: 8 - 10 bit
    - Aperture size: 5 mm x 5 mm (512 x 512 pixel, 7.9 micron pixel pitch)
    - Power consumption: 50 mw - 250 mw, varies with frame size
  - Imaging Lens
    - 1 cm diameter, 50 cm focal length, light-weight plastic lens
    - Mass: 3 gm
- Customized packaging
  - A customized miniature digital camera would be achieved by integrating a imaging lens on top of a camera-on-a-chip circuit board with the following specifications
    - Mass: 20 gram
    - Power consumption: < 250 mW
    - Speed: 30 - 100 frames/sec

    The above includes mass margin for a innovative stereo camera package to be designed using a dual lens image input fused on to a single APS imaging chip

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# Candidate APS Imaging Chips

**Two Candidate State-of-the-art Camera-on-a-chip Active Pixel Sensors Have Been Identified:**

PB 159 (by Photobit Inc.)

- Array Format: 512H x 384V
- Pixel Size: 7.9 μm x 7.9 μm
- Optical Format: 1/4 inch
- Frame Rate: 0 -39 frames/sec
- Power: 50 mW
- Sensitivity: 1 lux
- Output: 8 bit

PB 720 (by Photobit Inc.)

- Array Format: 128H x 720V
- Pixel Size: 7.9 μm x 7.9 μm
- Optical Format: 2/3 inch
- Frame Rate: 0 -60 frames/sec
- Power: 250 mW
- Sensitivity: 1 lux
- Output: 10 bit

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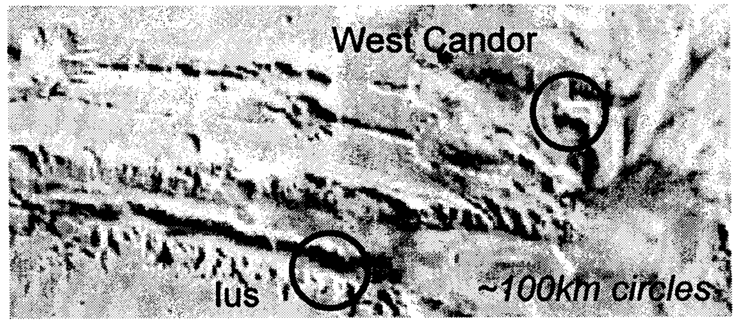
# Biomorphic Glider Surface Measurements

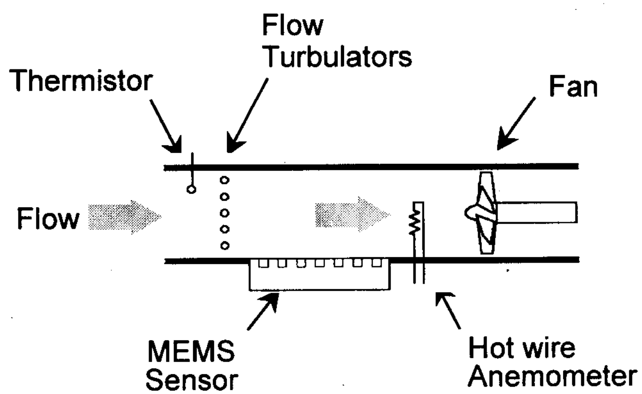
- **Large Number of Samples, Coverage and Diversity**
  - Total number of sites = number of gliders
  - Total area ~ 100km circle, permits broad area coverage of interesting geological regions




- **Distributed In Situ Experiments**
  - Chemical Composition

Gas Source

- Evolved gasses, (heat activated)
- Chemical reaction
- Drill probe, H2O / CO2 ice concentration vs. soil depth



# Biomorphic Glider Surface Measurements

- **Long Term Distributed Surface Observations**
  **(diurnal variation of relevant parameters)**
  - Seismic Measurement (accelerometers)
  - Atmospheric Pressure (pressure transducer)
  - Temperature (thermistor)
  - Solar Irradiance (solar cell)
  - Near-IR sensor to help differentiate water ice clouds from dust clouds

  (Would require additional solar cells for power)

- **Imaging**
  - Potential for interesting data if camera survives landing:
    - images showing local variation in soil / rock / terrain roughness on a scale relevant to rover mobility for future missions
    - local landscape images taken from perspective not obtainable from orbit from areas not accessible by rover

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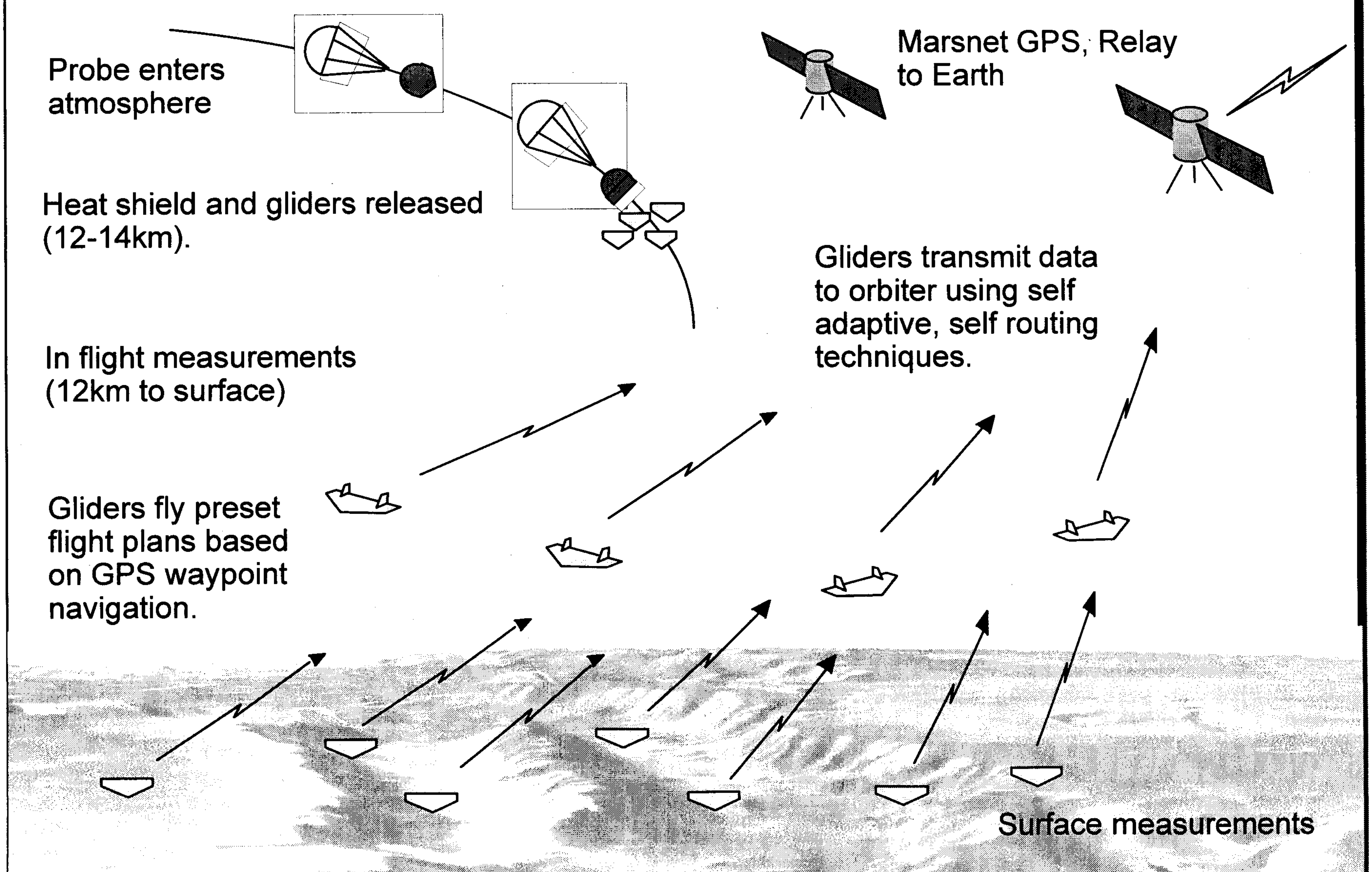
# Biomorphic Issues for Future Incorporation

- **Glider Navigation**
  - Simple => Flight plan / navigation based on sun angle (similar to bees) or GPS position
  - Intelligent => Use camera data to steer to interesting targets, neural site selector logic unit
  - Cooperative => Communications between gliders to maximize target diversity.
- **Glider Performance**
  - Soaring techniques => Glider performance (range and duration) can be greatly extended by taking advantage of atmospheric air currents much in the same way soaring birds use orthographic and convective currents to sustain flight for long periods of time and to cover great distances without flapping. (probably not very useful on Mars but may be of great value on Jupiter or Venus)
- **Flight Controls**
  - Possibility of capturing sensory-flight control mapping transformation onto neural chips will be explored to obtain goals of damage tolerance/adaptive controls

# Biomorphic Glider Deployment/Telecommunication Concept (long term)

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# Glider Navigation Strategy (long term)

- **GPS Navigation**
  - Requires miniature GPS technology for gliders and Marsnet implementation
  - Each glider has unique flight plan using GPS waypoint navigation referenced to actual release point
  - Functional day or night
- **Adaptive Targeting to Maximize Science Return**
  - Gliders provided list of prioritized science target signatures
  - Glider flight trajectory can be adjusted to take advantage of high priority science targets captured in camera / sensor FOV
  - During comm process, each glider notes which class of target neighbors are focused on and determines need to adjust flight plan to maximize target diversity (eliminates problem of all gliders going after same high priority target)

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# Glider Comm Strategy (long term)

- **Glider Based Self Adaptive Phased Array (possible innovation)**
  - **Motivation**
    - Mass and volume constraints limit RF capability of individual glider to communicate directly with orbiter
    - Gliders modulated in phase have sufficient capability to communicate with orbiter
    - Total mission mass, cost, and volume can be minimized (or number of gliders maximized) by eliminating need for relay
    - Comm strategy is now very fault tolerant (I.e. not dependent on any single system to operate, can tolerate failure of several gliders without impacting overall performance)
  - **Approach**
    - Use self adaptive phased array techniques
    - Orbiters / GPS system used as reference, can use two "chirps" in succession to determine modulation phasing for each individual glider
    - Gliders communicate between themselves and share data to be transmitted before transmitting to orbiter
    - May require partitioning (grouping) of gliders, each with separate target orbiter, to handle data rates
    - Will require significant memory and processing capability on-board glider

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# Glider Locating Strategy (long term)

- **Position Determined using GPS**
  - Requires miniature GPS technology for gliders and Marsnet implementation
  - Functional day or night
- **Position Inferred from Data**
  - Entry point + flight plan + glider performance + pressure altitude + images => GPS position validation

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# Physics of Flight - Aircraft

## The minimum flight speed determined using:

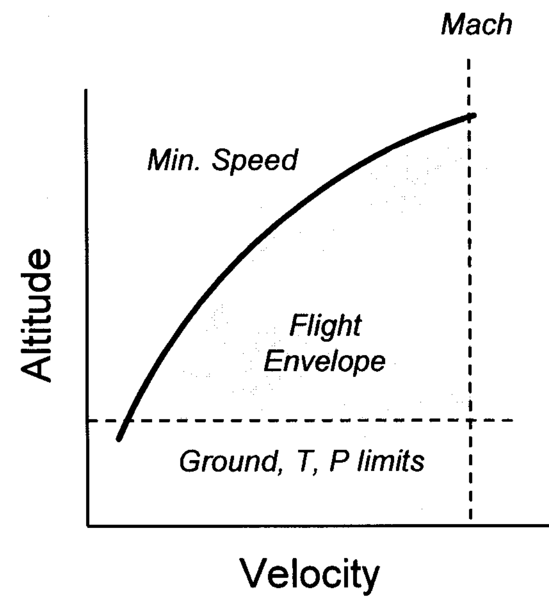
$$V = \sqrt{\frac{2\,W/S}{\rho\,C_l}}$$

W (weight) = Mass * Gravity, [lower is better]

$\rho$ = Atmospheric density, [higher is better]

$C_l$ = Max. wing lift coeff., $f$(Re, M, config.)

S = Wing area, [big = low V, small for probe]




## The maximum allowable flight speed is determined by the speed of sound.

| | |
|---|---|
| Performance | At high transonic speeds the drag rises sharply |
| Stability | The aerodynamic center moves aft near M=1 |
| Measurement | Affected by shock wave |

*(Good idea to keep flight speeds below Mach = 0.6)*

## Lowest possible altitude is limited by:

| | |
|---|---|
| Ground | Cannot go below the surface |
| Temperature | Too hot for many system components (Venus) |
| Pressure | Pressure too high for certain components |

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# Flight on Mars

| *Parameter* | *Earth* | *Mars* | *Units* | *Effect (all else equal)* |
|---|---|---|---|---|
| **Gravity** | 9.8 | 3.7 | m/s^2 | Flight speed 61% that on Earth |
| **Atm. Density** | 1.225 | 0.017 | kg/m^3 | Flight speed 10 times that on Earth |
| **Vsound** | 340 | 228 | m/s | Maximum flight speed 67% lower than Earth |

| | |
|---|---|
| **Flight Regime** | Mach ~ 0.5, Re ~ 30,000 |
| **Atm. Winds** | Mean wind speeds on Mars ~ 20m/s, (TES),<br>Seasonal dust storms ~100m/s gusts,<br>Flight in winds close to flight speeds not a problem. |
| **Atm. Turbulence** | Design for sufficient control power to maintain platform stability. |

*Note:* *Values for gravity, density and speed of sound are given are at surface.*

*Flight regime, (Reynolds Numbers ~30,000, Mach ~ 0.6), is same as flight regime experienced by AeroVironment's high altitude aircraft propellers.*

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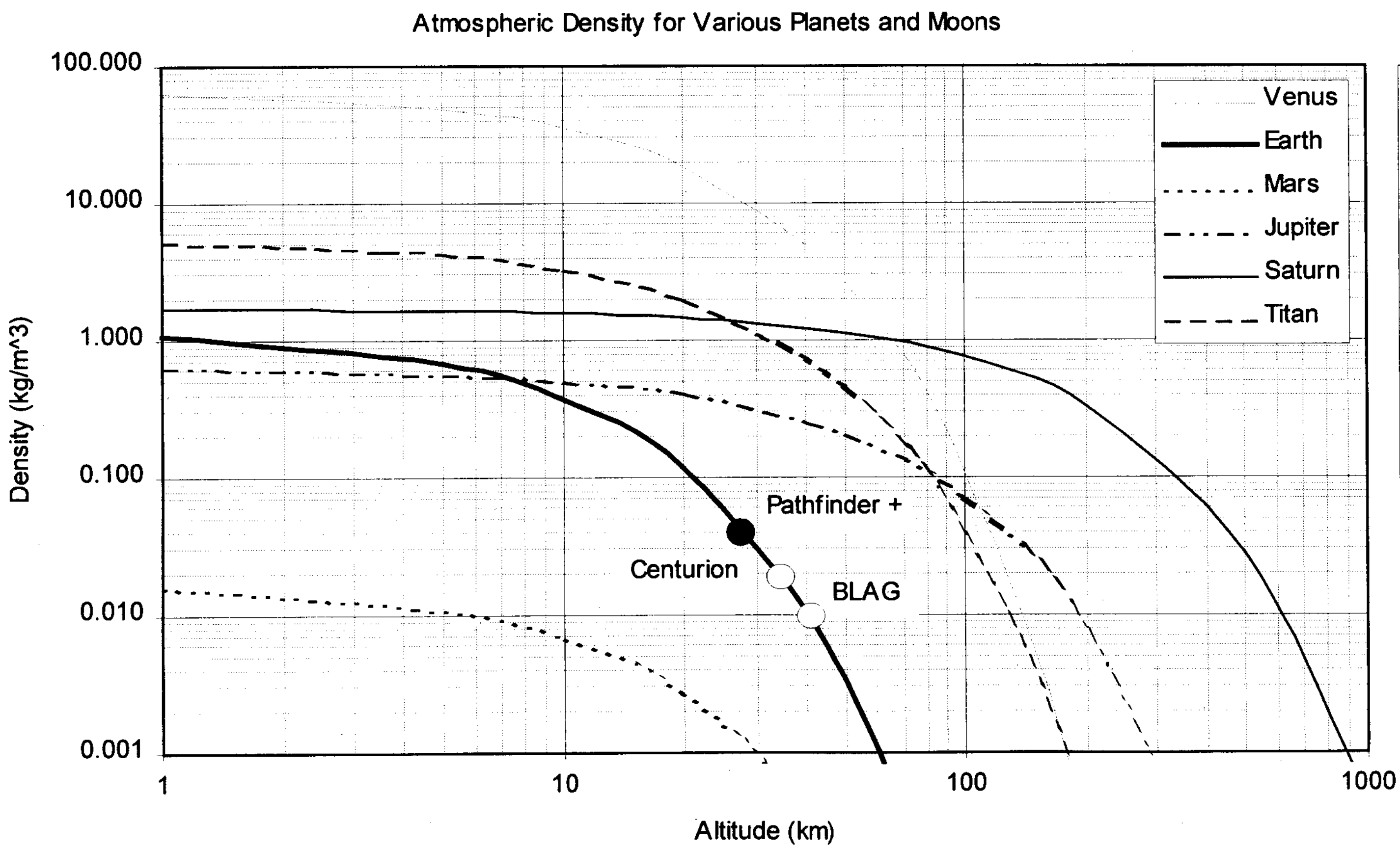
# Atm. Density for Selected Planets

- **Most planets have denser atmospheres than Earth.**
- **NASA programs are demonstrating flight at an air density similar to Mars.**




*On August 6, 1998, the NASA ERAST Pathfinder Plus, flew to over 80,000 ft.*

*In 2000, NASA ERAST Centurion will fly to over 100,000 ft.*

*In 1999, plans are being made to drop an autonomous glider from a balloon at 120,000ft (BLAG).*

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# Gravity for Selected Planets

| Planet | Gravity (m/s^2) |
|---|---|
| Venus | 8.90 |
| Earth | 9.81 |
| Mars | 3.75 |
| Jupiter | 25.05 |
| Saturn | 10.55 |
| Uranus | 8.89 |
| Neptune | 11.21 |
| Titan | 1.35 |

Gravity on most planets is similar to that on Earth.

Jupiter has 2.5 times the gravity on Earth resulting in a flight speed 61% higher than on Earth, all else equal. This should not be a problem due to the higher atmospheric density and high speed of sound.

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# Speed of Sound for Selected Planets

| Planet | Vsound (m/s) |
|---|---|
| Venus | 421.40 |
| Earth | 340.30 |
| Mars | 228.70 |
| Jupiter | 1256.90 |
| Saturn | 1298.80 |
| Uranus | 1353.50 |
| Neptune | 1342.30 |
| Titan | 194.30 |

The speed of sound is higher on most planets as compared to Earth. However, the atmospheres are denser so achieving subsonic flight speeds with reasonable mass loading should be relatively easy.

Mars and Titan have lower speed of sound than Earth. Since Mars also has a much thinner atmosphere, a subsonic aircraft will require low mass loading to avoid compressible effects. This does not appear to be a problem for Titan with a much denser atmosphere and lower gravity.

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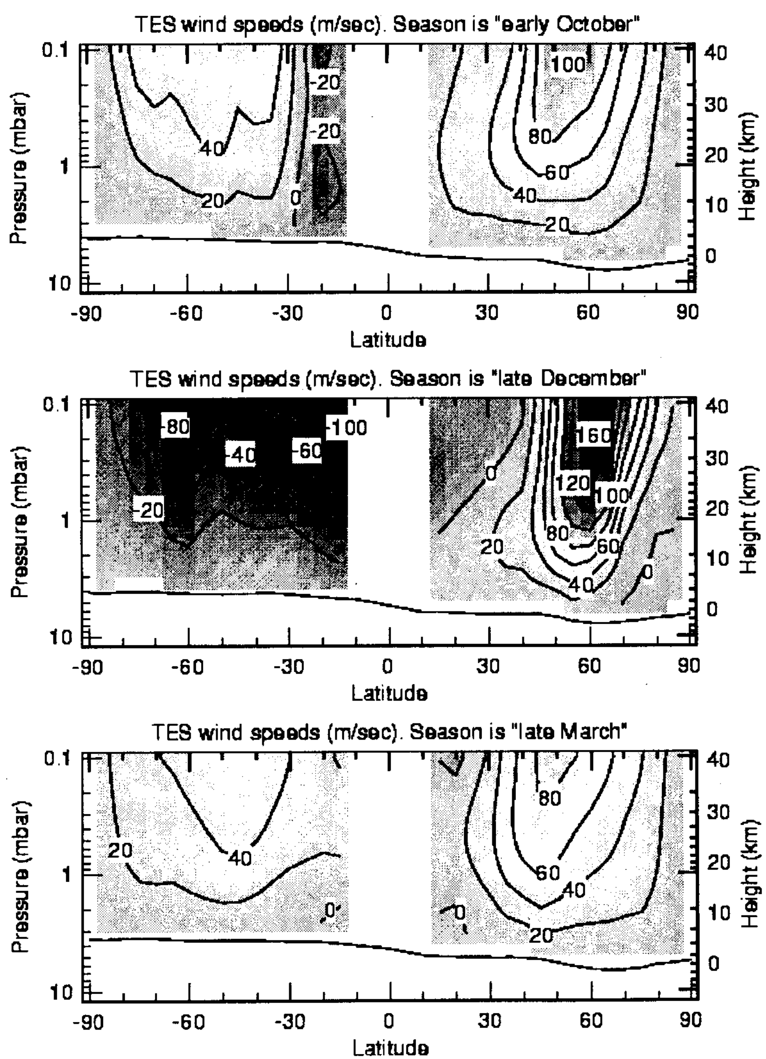
# Winds on Mars




## From thermal emission spectroscopy

- Peak wind speeds ~ 70m/s, seasonal in certain north latitudes.
- Average winds at 10km ~20m/s.
- Average winds near surface are less than 20m/s with seasonal gust fronts.

## Effect of winds on Biomorphic Gliders

- Impact on flight trajectory is to skew flight lines (I.e. performance enhanced downwind, degraded upwind).
- Gliders frequently fly on Earth in winds approaching flight speed.
- Sufficient control power to compensate for gust upsets near the surface should be included in designs.

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# Comparison of Biomorphic Flight System Concepts for Mars

## JPL-AEROVIRONMENT COLLABORATION

| *Parameter* | | *Class* Powered μFlyer | Glider (1) | Glider (2) | Seedwing Flyer |
|---|---|---|---|---|---|
| Lift Generation | | Wing | Wing | Wing | Rotating Wing |
| Method of Propulsion | | Propeller | Gravity | Gravity | Gravity |
| Energy Storage | | Li Battery | Altitude | Altitude | Altitude |
| Total Mass | (gm) | 57 | 75 | 57 | 57 |
| Payload Mass | (gm) | 6 | 47 | 32 | 52 |
| Wing Span | (m) | 0.194 | 0.25 | 0.194 | 0.19 |
| Wing Area | (m^2) | 0.019 | 0.021 | 0.019 | 0.12 |
| Volume | (cm^3) | 380 | 300 | 230 | 77 |
| Flight Speed | (m/s) | 84 | 90 | 84 | 6 |
| Range | (km) | 10 | 55 | 50 | 0 |
| Duration | (sec) | 120 | 650 | 700 | 790 |
| Glide Ratio | | 5.3 | 5.8 | 5.3 | 0 |
| Starting Altitude | (km) | 0 | 10 | 10 | 10 |

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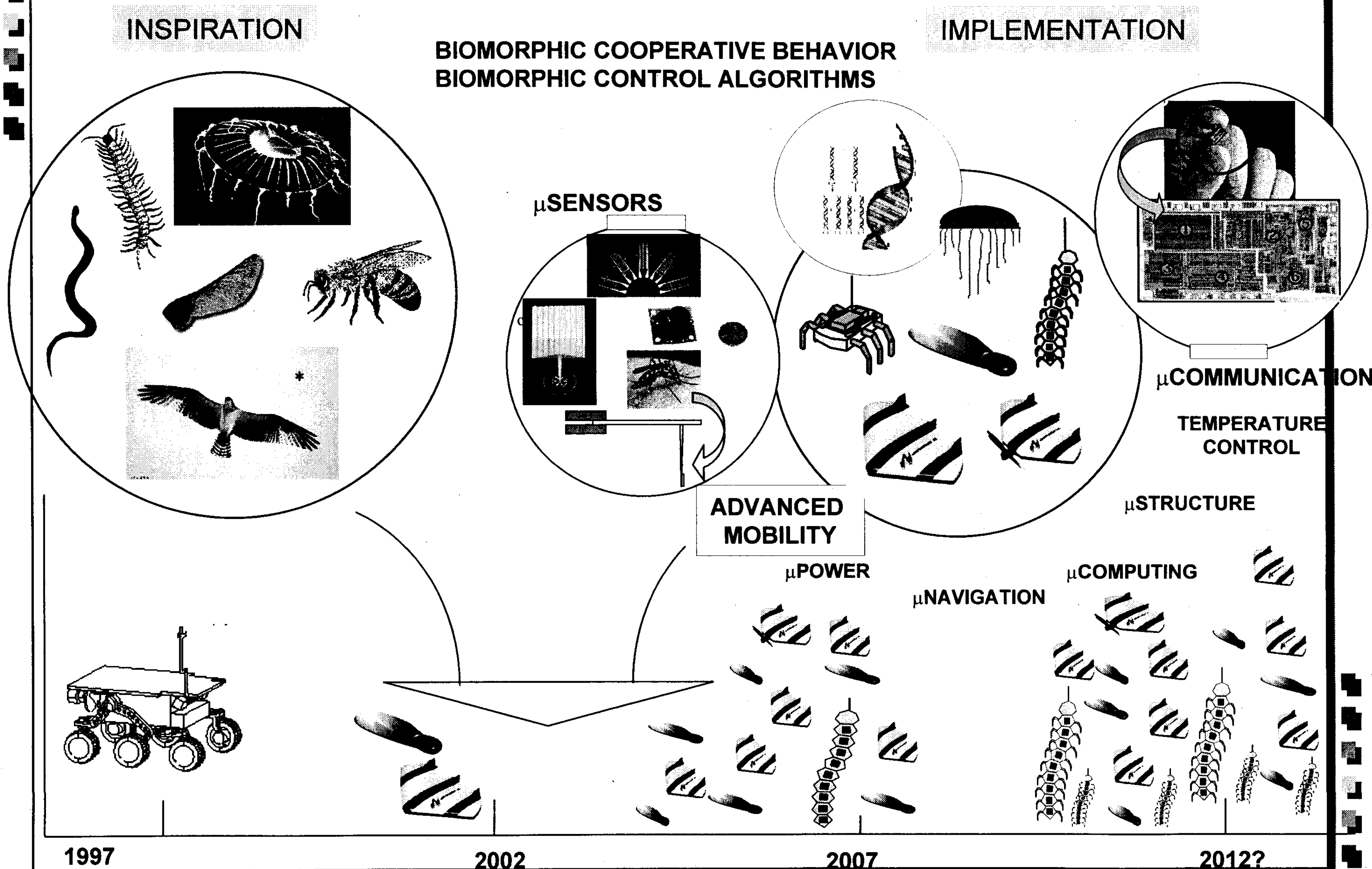
## 1998 STUDY RESULTS SUMMARY

Enabling better spatial coverage and access to hard to reach and hazardous areas at low recurring cost




*http://www.gregscott.com/rwscott/rwscott.htm

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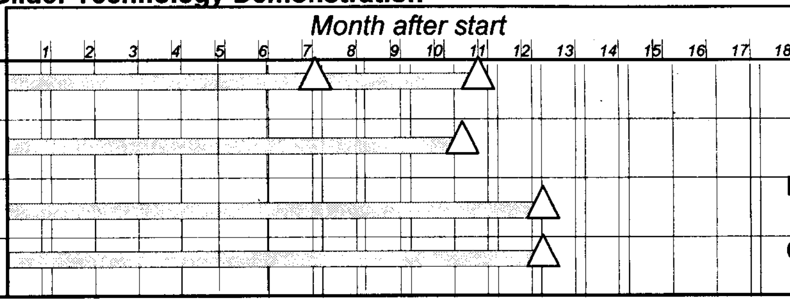
# Biomorphic Explorer Technology Development RoadMap

## Biomorphic Glider Technology Demonstration




| | |
|---|---|
| Payload Subsytem Design. | Atmospheric data sensors, miniature camera package for close-up imaging. |
| Deployment and Mission Architecture Selection | Probe /Balloon/Lander Deploy, Mission specific measurement strategies |
| Demonstrate small airframe flight with solar Navigation | Develop & demo solar navigation for small air frame glider with high payload fraction. |
| Telecom Subsytem Design. | Glider Transciever and relay telecom design |

## Biomorphic Subsystem Technologies

| | | |
|---|---|---|
| Payload: | Pressure transducer, Temperature sensor | Need MEMS sensor with range and accuracy, available |
| | Solar rad / sun position sensor | Combined solar meter and navigational aid. |
| | Chemical constituent sensor | E Nose, H, C, O species |
| | IR sensor | Need small, low power sensor. |
| | Camera | Identify suitable technology vendor. |
| | Surface experiments | Identify worthwhile surface measurements, develop plausible concepts (pH, H2O/CO2, ice content, minerology, pyrotechnic experiment) |
| Communications, Multiple Access Schemes | | Need small, efficient transmitter / receiver. |
| Cooperative Operation, Intraspecies, Interspecies | | Based on Bio-inspired behaviors in insect colonies |

## Biomorphic Advanced Studies

| | |
|---|---|
| Biomorphic Communications | |
| Bio-Mechatronic Designs: Reconfigurable Implementations | |
| Bio-Mimetic Power Generation/Conversion | |
| Plant Inspired Mobility | |
| Biomorphic Controls | |

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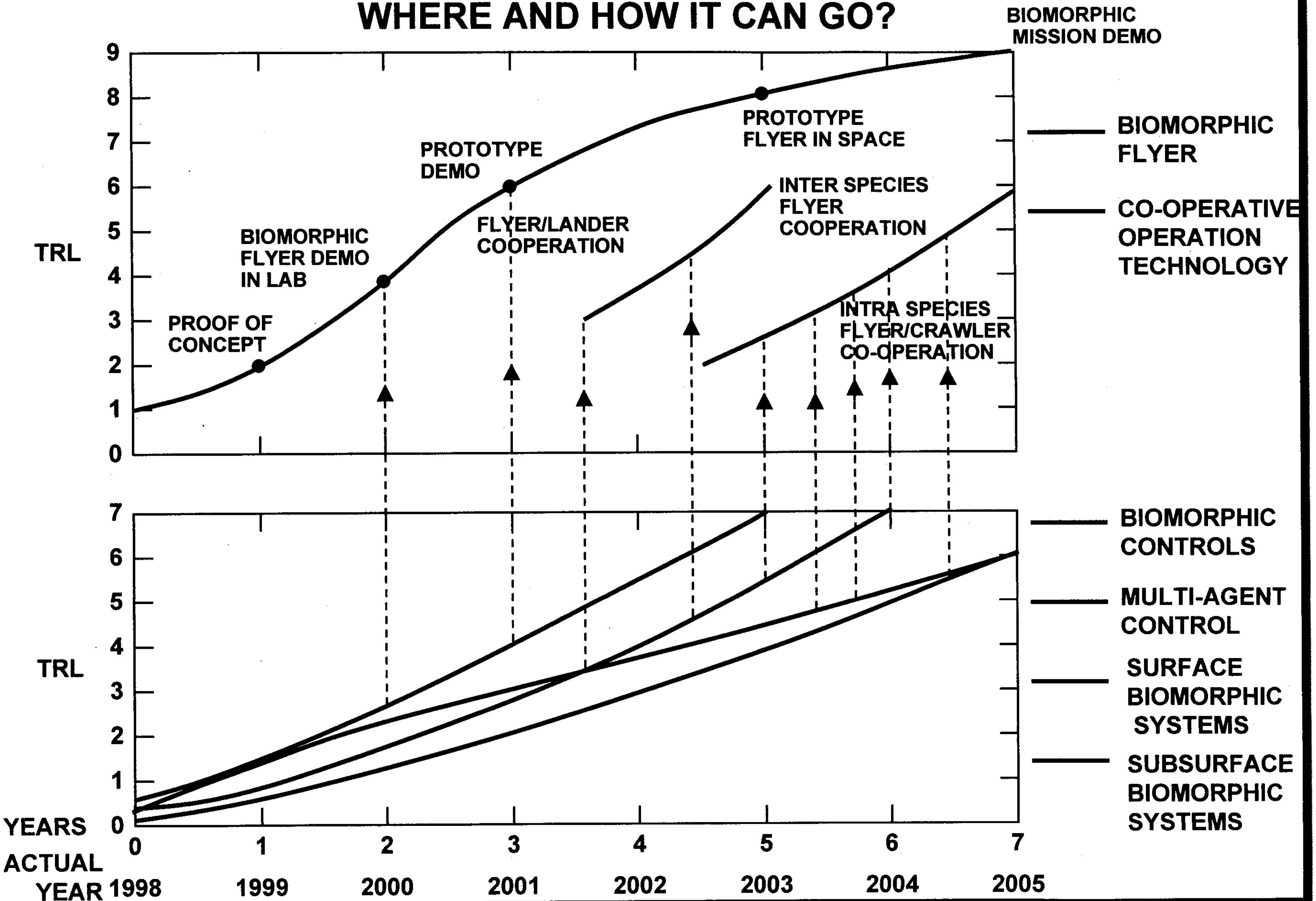
# BIOMORPHIC EXPLORER TECHNOLOGY

## WHERE AND HOW IT CAN GO?

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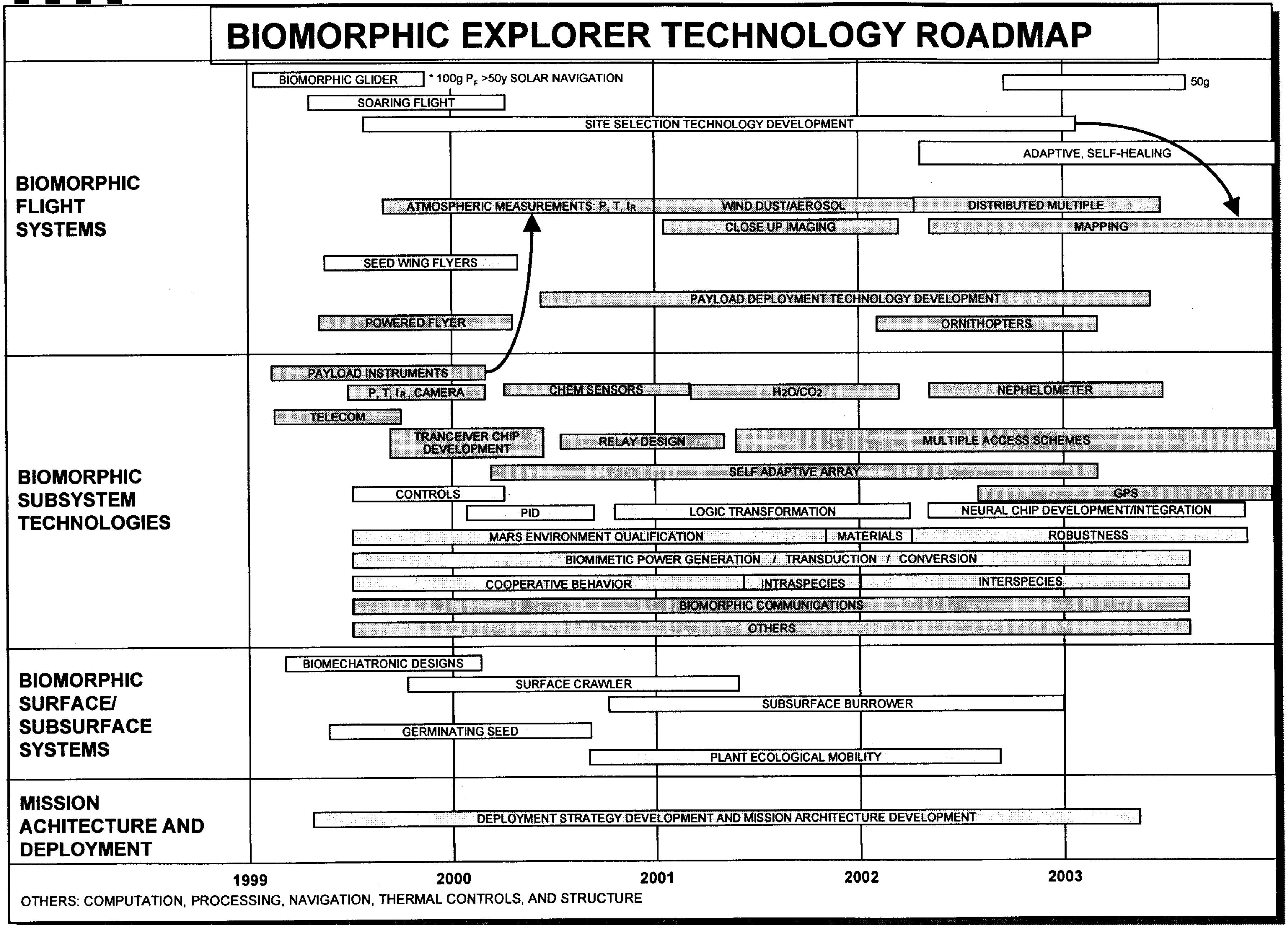


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# *CONCLUSIONS*

- BIOMORPHIC EXPLORERS IS A VIABLE TECHNOLOGY THAT WILL ENABLE NEW COOPERATIVE EXPLORATION MISSIONS

- BIOMORPHIC MARS GLIDER WITH FOLLOWING FEATURES
  - MASS < 100 g
  - PAYLOAD FRACTION > 50%
  - LARGE RANGE ~ 50-100 Km
  - SOLAR NAVIGATION

  IS SUCCESSFULLY DESIGNED, AERODYNAMICALLY POSSIBLE

- BIOMORPHIC GLIDER MISSIONS CAN BE IMPLEMENTED IN SEVERAL DIFFERENT SCENARIOS AND THEREFORE BIOMORPHIC EXPLORERS CAN BE SENT RAPIDLY IN THE MASS RESERVES OF UPCOMING ORBITER, LANDER OR BALLOON MISSIONS

- BIOMORPHIC EXPLORERS IS A TECHNOLOGY PUSH ON
  - MINIATURIZATION & INTEGRATION OF PAYLOAD
  - COOPERATIVE COMMUNICATION INNOVATIONS
    - monolithic transciever integration
    - dynamic networks of self routing optimal comm-interlinks
  - BIOMORPHIC FLIGHT SYSTEMS
  - BIOMECHATRONIC SURFACE SYSTEM INNOVATIONS

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